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SURFACE WATER SECTION

SWS Contract Report 495

ENVIRONMENTALLY ACCEPTABLE MORPHOLOGIC CHANNEL DESIGN OF STREAMS WITH SMALL TO MEDIUM-SIZED DRAINAGE AREAS

by Sally McConkey Broeren and Krishan P. Singh

Prepared for the
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INTRODUCTION

Streams in Illinois with small drainage areas have been extensively modified to improve drainage for agriculture and to abate flooding in urban settings. The common practice for more than 100 years has been to widen, deepen, and straighten water courses to accelerate drainage and provide increased in-channel storage during flood events. In natural streams, riffle and pool sequences in both straight and meandering streams create a diversity of habitats necessary to support fish and other riverine life forms in a viable aquatic ecosystem. These features are lost in channelized streams, where the typical channel design results in a uniform cross section. Bank instability and channel erosion are other consequences of straight, uniform channel design. Recognition of the adverse impacts of traditional channelization practices has led to government initiatives to develop guidelines for channel modification practices that are more environmentally sensitive (IEPA, 1989). Artificial riffles and pools constructed in channelized streams have successfully contributed to revitalizing stream ecology. However, little information is available on the dimensions and materials appropriate for the design of riffle-pool sequences. A methodology is needed for assessing the beneficial impact of proposed channel rehabilitation projects in terms of increasing the availability of suitable aquatic habitat. Such assessments would provide information vital in evaluating designs before their implementation.

This study had four purposes:

1) To collect detailed information defining the bed structure of natural streams in the study watershed.

2) To develop general basinwide relationships for predicting expected channel characteristics of streams throughout the network.

3) To explore the use of state-of-the-art habitat assessment models for evaluating the benefits of restoration of riffle-pool sequences in terms of availability of suitable aquatic habitat.

4) To collect and present data on the cost of channel modification work.

The Sangamon River Basin in central Illinois was selected for this study. This basin is typical of stream networks in much of Illinois, and the relations developed will apply to the Sangamon Basin directly and to other basins with similar physiography. The Sangamon Basin has been the subject of numerous studies, and previously collected data provide a basis for judging the representativeness of samples as well as for independent verification of basin wide relationships. Three natural reaches representing a range of drainage areas between 50 and 400 square miles (sq mi) and spanning three riffle-pool sequences were selected for field data collection. Information was collected in each reach on channel shape and bed materials, as well as on width, depth, and velocity of flow at three different discharges. This information was used to identify the channel characteristics of natural streams in the basin and to verify and improve relations used in a previously developed basinwide flow and aquatic habitat model of the Sangamon Basin (Singh et al., 1986). The data and relationships resulting from the field investigation, as well as sample output from the flow and aquatic habitat model, are presented. In addition to the specific data collected for the Sangamon Basin, cost data for various aspects of channel modifications and rehabilitation are also presented.

Acknowledgments

This study was supported by the Office of Research and Planning and the State Water Survey Division of the Illinois Department of Energy and Natural Resources. Linda Vogt of the Office of Research and Planning served in a liaison capacity during the course of the study. This report was prepared under the general direction of Richard G. Semonin (Chief) and Michael L. Terstriep (Head of the Surface Water Section), Illinois State Water Survey. Particular recognition goes to Elizabeth Esseks, who acted as field supervisor for data collection, performed data entry and calculations, and prepared computer graphics. Kathleen Brown typed and formatted the final report, Gail Taylor edited the report, and Linda Riggin prepared the final graphics.

BASIN DESCRIPTION

The Sangamon River Basin is located in central Illinois. The Sangamon River is a tributary of the Illinois River; at its confluence with the Illinois River, it has a drainage area of 5,452 sq mi. The stream network has three main branches: the Sangamon (main stem above Riverton, drainage area 1,445 sq mi); the South Fork Sangamon (drainage area 883 sq mi); and Salt Creek (drainage area 1,856 sq mi). Because of hydrologic and geomorphologic differences in the watersheds of these three streams, the Sangamon River Basin may be subdivided into three hydrologically homogeneous basins.

Five major artificially created reservoirs are located within the Sangamon River Basin. Four of these are on tributaries to the main branches, and one is on the main stem of the Sangamon River. Lake Springfield, Sangchris Lake, and Lake Taylorville are on tributaries to the South Fork Sangamon. Clinton Lake is located in the Salt Creek Basin. Lake Decatur is located on the Sangamon River.

Hydrology

Singh (1971) divided the Sangamon River Basin (excluding the Havana Lowlands) into three relatively hydrologically homogeneous basins: Sangamon (above Riverton), South Fork Sangamon, and Salt Creek. The watershed of the Sangamon River above Riverton is referred to as the Sangamon Basin hereafter in this report. Equations defining discharge as a function of drainage area for selected flow durations for each of the three basins are given by Singh et al. (1986). These basin discharge equations provide a consistent method of computing discharge for a selected flow duration at any location within the stream network of the basin. The form of the equations and coefficient values for each of the three basins are given in Table 1. Similar hydrologic divisions are presented by Knapp et al. (1985) along with discharge flow-duration equations. The equations presented by Knapp et al. (1985) are used in the Sangamon Basin Interactive Flow Model, which is a microcomputer package developed for the Illinois Department of Transportation. The model is used to compute discharges corresponding to various return frequencies and durations. The data used to develop these equations, as well as the form of the equations, differ from the equations given by Singh et al. (1986). The two sets of discharge equations were compared by computing discharges corresponding to flow durations between 5 and 95 percent for each study site. The discharges computed for each study site are plotted versus flow duration in Figure 1. Within the range of flows from 40 to 90 percent flow

Table 1. Basin Regression Coefficients for Discharge

$$\log(VAR) = a_{ij} + b_j(\log DA)$$

	Regression coefficients			
	Sangamon	*South Fork Sangamon*	*Salt Creek*	
VAR(j)	$a_{1,j}$	a_{2j}	a_{3j}	b_j
Q(99)	-5.1183	-5.5025	-4.4167	1.9488
Q(95)	-3.6001	-4.0998	-3.1499	1.5833
Q(90)	-2.8257	-3.1131	-2.4983	1.3909
Q(80)	-2.2448	-2.3825	-2.0045	1.2864
Q(70)	-1.7144	-1.8431	-1.5770	1.2070
Q(60)	-1.1887	-1.3260	-1.1065	1.1220
Q(50)	-0.7843	-0.9254	-0.7571	1.0640
Q(40)	-0.5583	-0.6833	-0.5453	1.0507
Q(30)	-0.3554	-0.4473	-0.3559	1.0433
Q(20)	-0.0880	-0.1742	-0.1181	1.0222
Q(10)	0.1903	0.1581	0.1424	1.0175
Q(5)	0.4516	0.4686	0.3926	0.9991
Q(1)	1.0833	1.1219	1.0392	0.8964

Note: DA = drainage area in sq mi
j = flow duration in percent
Q(j) = discharge, in cfs, having flow duration j

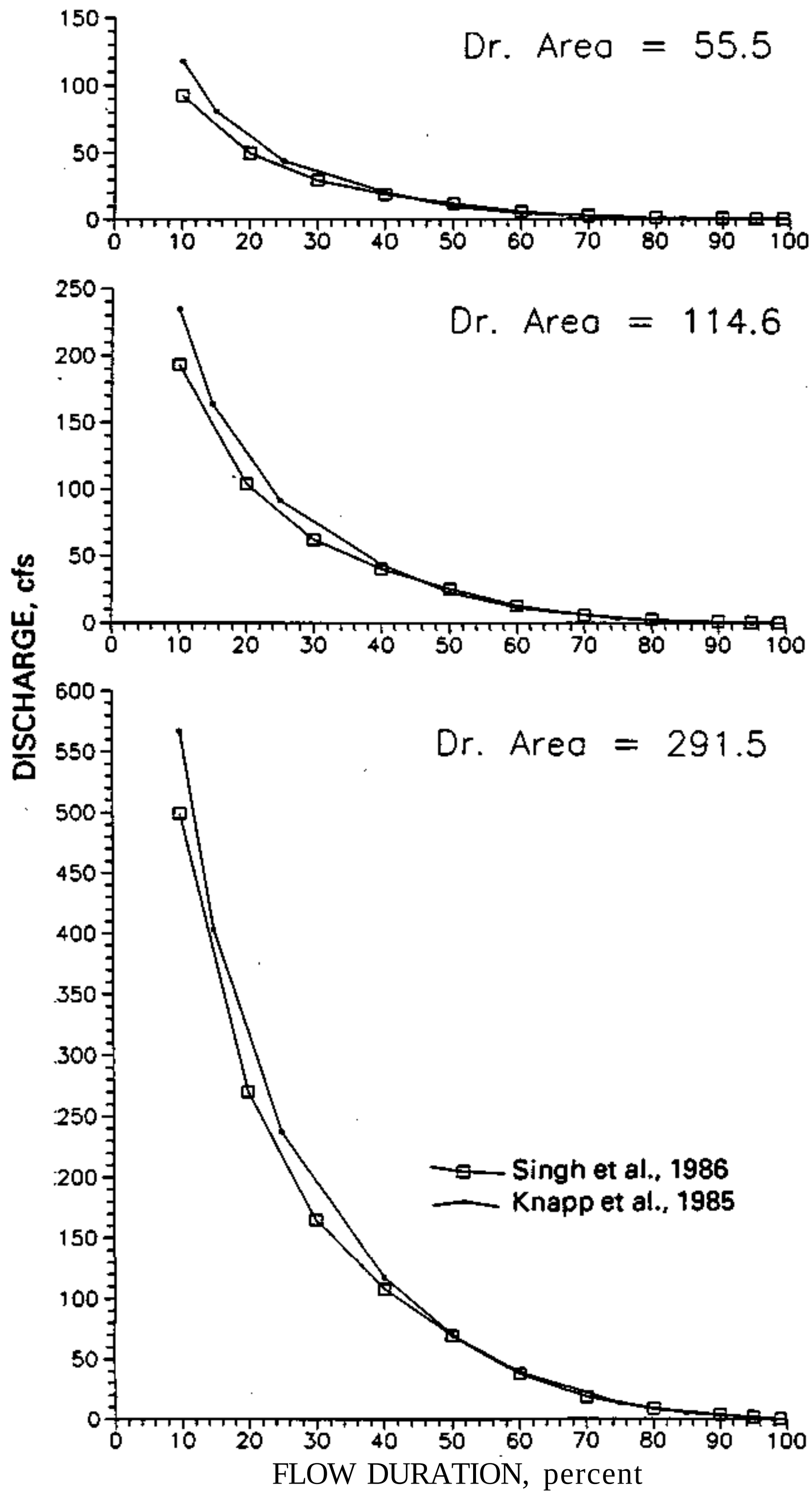


Figure 1. Discharge versus flow duration for the three study drainage areas

duration (medium to low flows), there is close agreement between the predicted values of discharge at the study sites. At higher flows there is a greater departure between the predicted values, but as a percent of the total discharge the difference is small.

The form of the discharge flow-duration equations presented by Singh et al. is best suited for development of other relations used to model flow characteristics in a basin and thus were used in this study. However, as there appears to be close agreement between the results of the two equations, information generated by the Sangamon Basin Interactive Flow Model can readily be integrated with the products of this study.

Geomorphology

The geomorphology of the Sangamon River Basin is discussed by Leighton et al. (1948), Singh and Stall (1971), Singh et al. (1986), and Knapp et al. (1985). The history of glaciation across the basin plays an important role in explaining the differences in basin characteristics. Two physiographic regions cover the basin: the Springfield Plain, created during the Illinoian glacial advance, which covers about 60 percent of the entire basin; and the Bloomington Ridged Plain, created during the more recent Wisconsinan glaciation, which covers the rest. The upper portion of the Salt Creek Basin and the upper portion of the Sangamon Basin (to Decatur) lie within the Bloomington Ridged Plain. The South Fork Sangamon Basin lies entirely within the Springfield Plain. The demarcation of the two plains relative to the entire Sangamon River Basin is shown in Figure 2; the demarcation zone is referred to as the Shelbyville Moraine. Observed variations in low flows in the three basins may be traced to the glacial history of the region. The Salt Creek and Sangamon Basins have soils with higher permeability, larger drift thickness, and more deeply entrenched streams. These conditions contribute to higher baseflows. The South Fork Sangamon Basin has soils that are less permeable (providing less water retention for slow release into streams), lesser drift thickness, and shallower entrenchment of streams, thus reducing subsurface and ground-water accretion to the streams. These conditions contribute to lower baseflows.

Hydraulic Geometry Relations

Studies of channel morphology have shown that channel width, cross-sectional area, substrate particle size, and riffle spacing are related to drainage area or stream length by empirical expressions. Leopold and Maddock (1953) first formalized observations defining variations in width (W), depth (D), and velocity (V) of flow at a station (a single location along a stream) as power functions of discharge (Q) of the form

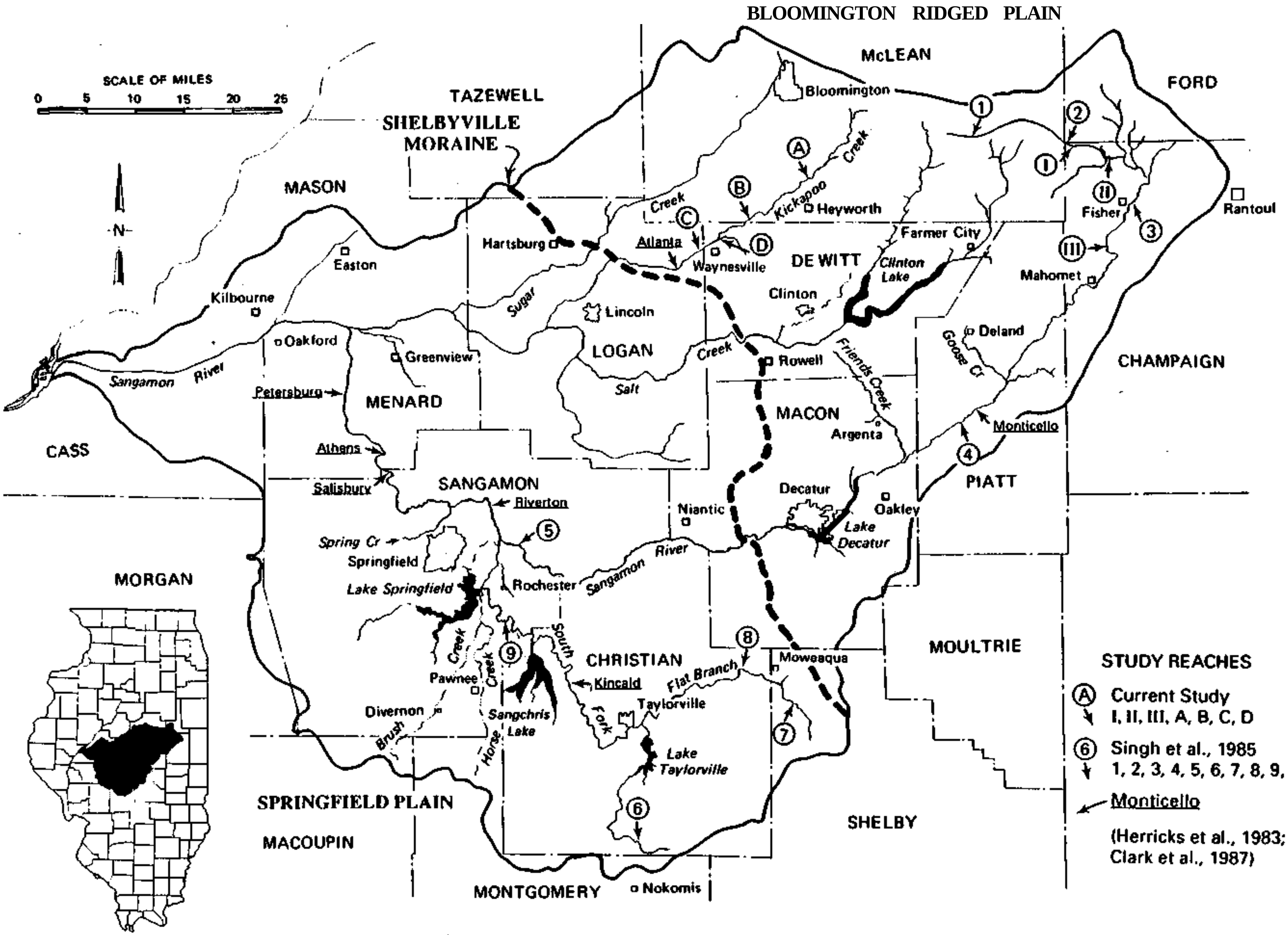


Figure 2. Sangamon River Basin

$Var = aQ^b$, Var = W, D, or V. Similar power functions express the trend of increasing W, D, and V with drainage area for a constant frequency of discharge. Stall and Fok (1968) expanded on this concept and developed relations for hydraulic parameters as a function of decimal flow duration (F) and drainage area (DA) of the form: log(Var) = a + bF + c(log DA).

The expressions proposed by Stall and Fok were used by Singh et al. (1986) to develop hydraulic geometry equations for the Sangamon, South Fork Sangamon, and Salt Creek Basins. These equations were developed by using the discharge versus drainage area equations for various flow durations, as well as station equations determined from width, depth, velocity, and discharge measurements at U.S. Geological Survey (USGS) gaging stations. A single equation for each hydraulic parameter (W, D, and V) defines it in terms of drainage area and flow duration between 10 and 90 percent for any stream in the basin. The flow durations are derived from daily flows for the period of record.

The hydraulic geometry equations for each basin were re-examined in this study. The product of W, D, and V must equal Q to satisfy the principle of continuity. Using the logs of the variable, this may be written as: log W + log D + log V = log Q. Substituting the form of the hydraulic geometry relations used by Stall and Fok for W, D, and V and the flow-duration equations for Q, this can be expressed as:

$$(a_w+a_d+a_v) + (b_w+b_d+b_v)F + (c_w+c_d+c_v) \log DA = a_{ij} + b_j \log DA \qquad (1)$$

where the subscripts w, d, and v refer to hydraulic geometry equation coefficients determined for width, depth, and velocity; the i and j subscripts for the discharge equation are as defined in Table 1; and j corresponds to the decimal flow duration F. Thus this equation must be satisfied for each flow duration. Inspection of the above equation shows that a_{ij} is analogous to $(a_w+a_d+a_v) + (b_w+b_d+b_v)$ F, and bj is analogous to $(c_w+c_d+c_v)$. Inspection of the a_{ij} and b_j coefficients for the discharge equations given in Table 1 demonstrates that they vary with flow duration for each basin. Therefore the c coefficients in the hydraulic geometry expression must also vary with flow duration. An alternative form for the hydraulic geometry relations which allows the coefficient for the parameter log (DA) to vary with flow duration and to satisfy this condition is:

$$\log Var = a + bF + (c + dF) \log DA \qquad (2)$$

Substituting this expression in the summation of log W + log D + log V, the following equations can be written expressing criteria for satisfying continuity:

$$a_{ij} = (a_w+a_d+a_v) + (b_w+b_d+b_v)F \tag{3}$$

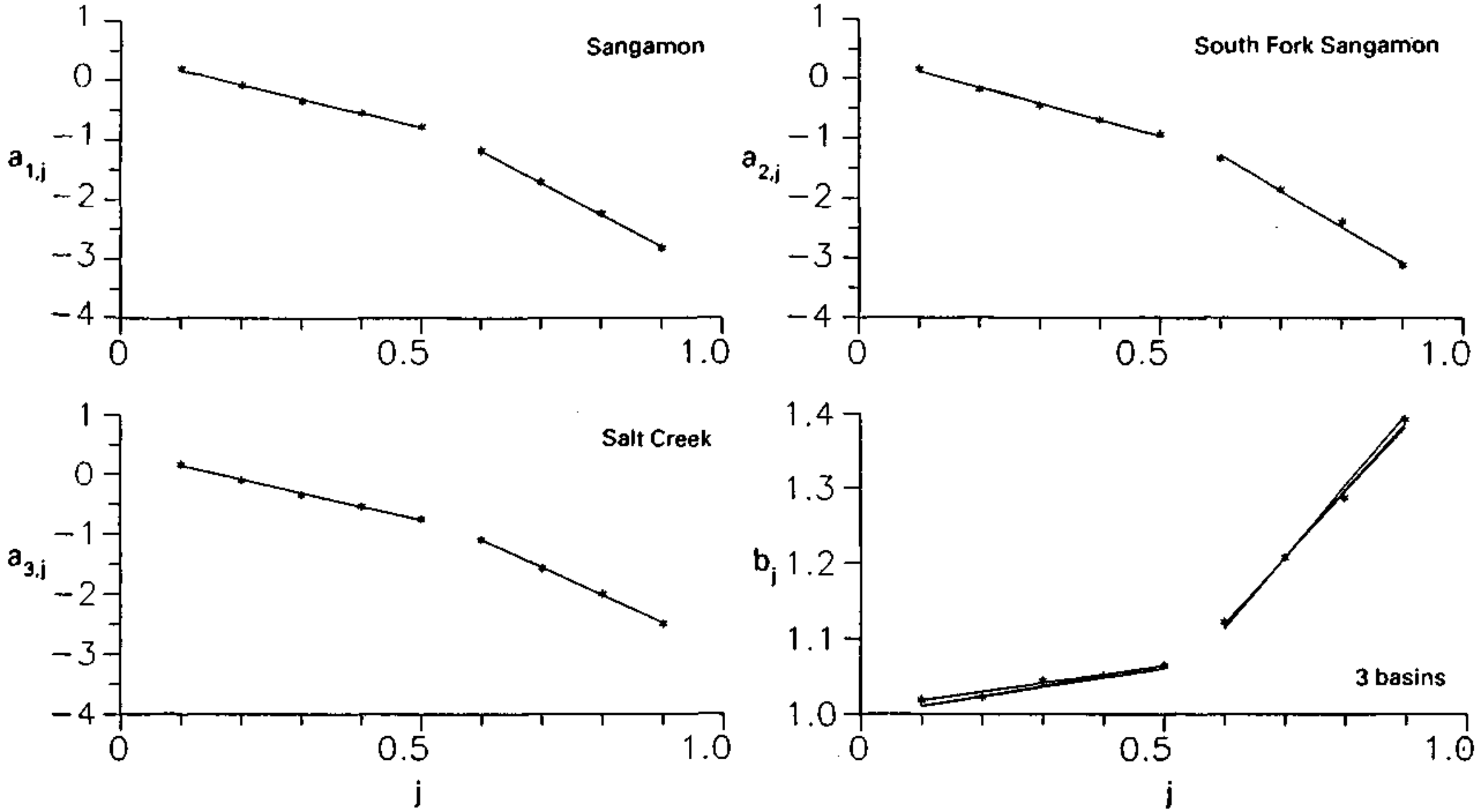
$$b_j = (c_w+c_d+c_v) + (d_w+d_d+d_v)F \tag{4}$$

To satisfy these equations, a_{ij} and b_j must vary linearly with flow duration. Figure 3 shows plots of the a_{ij} and b_j coefficients from Table 1 versus flow duration (j). It can be observed from the plots that there is a linear variation of these coefficients; however, there is a break in the slope between flow durations 50 and 60 percent. The basin hydraulic geometry equations were redeveloped, with station data regrouped into two sets corresponding to flow durations from 10 to 50 percent and 60 to 90 percent. Multiple regression analyses were performed to determine the coefficients for basin hydraulic geometry equations in the form of equation 2. The coefficients for each basin are given in Table 2.

The conditions of equations 3 and 4 were checked by summing the appropriate hydraulic geometry equation coefficients for each range of flow durations and each basin, and then substituting these values in equations 3 and 4. These linear equations are shown with solid lines in Figure 3. These equations provide a very close approximation of the linear trend of the a and b coefficients from the flow-duration equations. The redeveloped hydraulic geometry equations are used in the remainder of this report.

Stream Slopes

Contour elevations read from U.S. Geological Survey topographic quadrangles were plotted versus distance from the basin divide for the Sangamon River, the Flat Branch (tributary to the South Fork Sangamon), and Kickapoo Creek (tributary to Salt Creek). On the basis of these streambed profiles, changes in longitudinal bed slope were noted for each river, and the slopes of river segments computed. Bed elevations versus distances from the basin divide for these rivers are shown in Figures 4 and 5. In Figure 4, the entire Sangamon River from the basin divide to its confluence with the Illinois River is shown. Also shown on this plot are the confluences with Salt Creek and the South Fork Sangamon River and the location of the Lake Decatur dam. The locations of the three sites that are the subject of this study are identified in the figure as I, II, and III. The locations of other reaches of the river studied in prior projects are



* Coefficient value from table 1
— Straight line derived from basin hydraulic geometry equation coefficients
j = Decimal flow duration
Subscripts 1, 2, and 3 refer to Sangamon, South Fork Sangamon, and Salt Creek, respectively.

Figure 3. Discharge equation coefficients versus flow duration

Table 2. Basin Hydraulic Geometry Coefficients for Each Basin

$\log(VAR) = a + bF + (c + dF) \log DA$; F = decimal flow duration;
DA = drainage area (sq mi)

VAR	*a*	*b*	*c*	*d*	*adjR^2*	*S_e*
Sangamon, F = 0.90, 0.80, 0.70, 0.60						
W	1.454	-2.107	0.352	0.356	0.97	0.06
D	0.213	-1.794	0.232	0.200	0.89	0.09
V	0.407	-1.526	0.009	0.323	0.62	0.12
Sangamon, F = 0.50, 0.40, 0.30, 0.20, 0.10						
W	0.476	-0.397	0.584	-0.060	0.93	0.09
D	-0.501	-0.722	0.469	-0.153	0.91	0.09
V	0.417	-1.268	-0.047	0.329	0.21	0.12
South Fork Sangamon, F = 0.90,0.80, 0.70,0.60						
W	2.095	-3.308	0.124	0.763	0.98	0.08
D	0.752	-2.872	0.140	0.507	0.96	0.08
V	-0.482	0.129	0.283	-0.327	0.25	0.11
South Fork Sangamon, F = 0.50, 0.40, 0.30, 0.20, 0.10						
W	0.854	-1.260	0.438	0.248	0.96	0.07
D	-0.406	-0.989	0.487	-0.068	0.96	0.07
V	-0.0572	-0.437	0.077	-0.056	0.50	0.08
Salt Creek, F = 0.90, 0.80, 0.70, 0.60						
W	1.825	-2.667	0.163	0.699	0.98	0.04
D	0.671	-2.152	-0.035	0.480	0.92	0.05
V	-0.833	0.207	0.454	-0.287	0.72	0.08
Salt Creek, F = 0.50, 0.40, 0.30, 0.20, 0.10						
W	0.529	-0.294	0.563	-0.042	0.92	0.08
D	-0.324	-0.401	0.338	-0.182	0.71	0.11
V	0.146	-1.551	0.099	0.350	0.85	0.06

Note: adj R^2 = unbiased coefficient of determination
S_e = standard error
W = width; D = depth; V = velocity

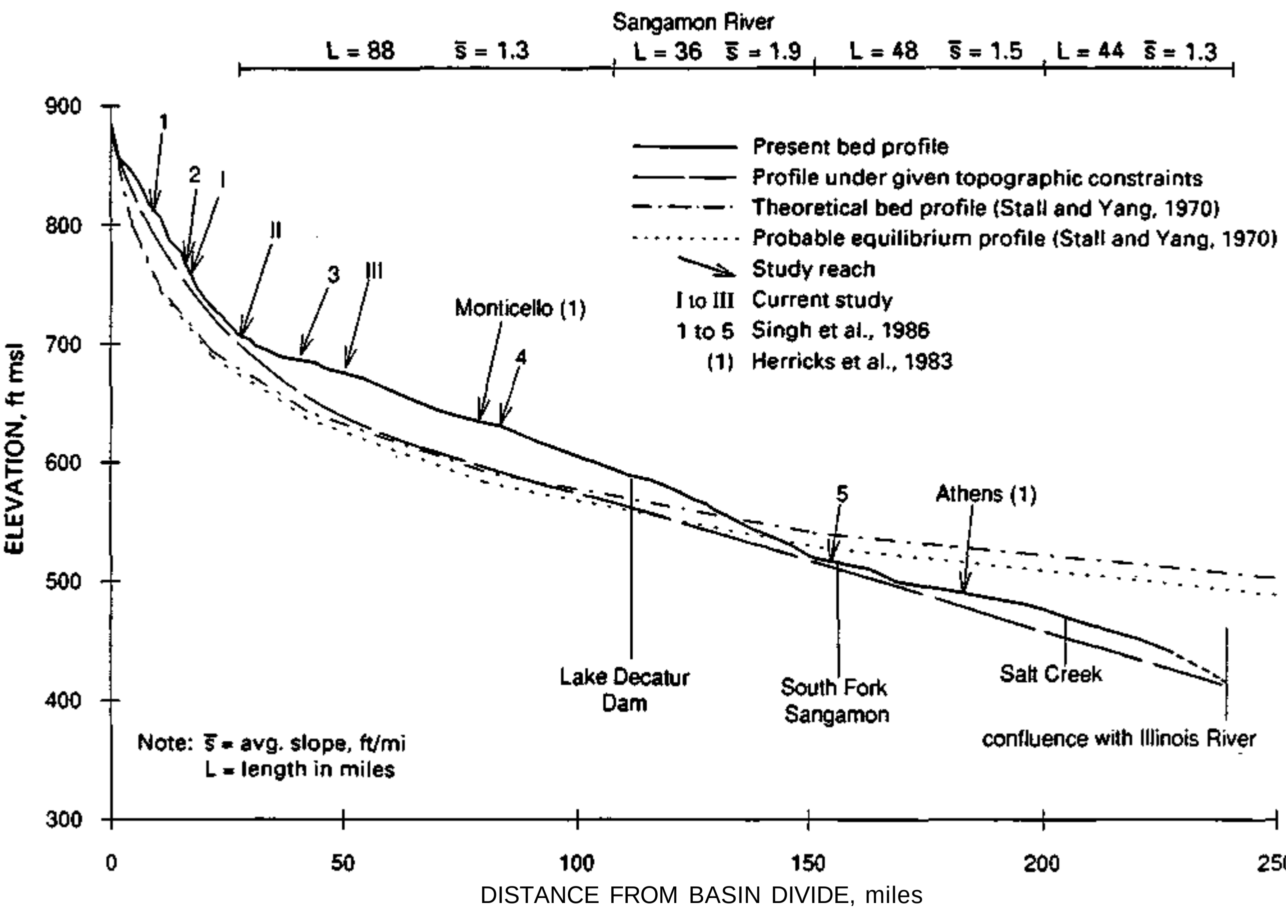
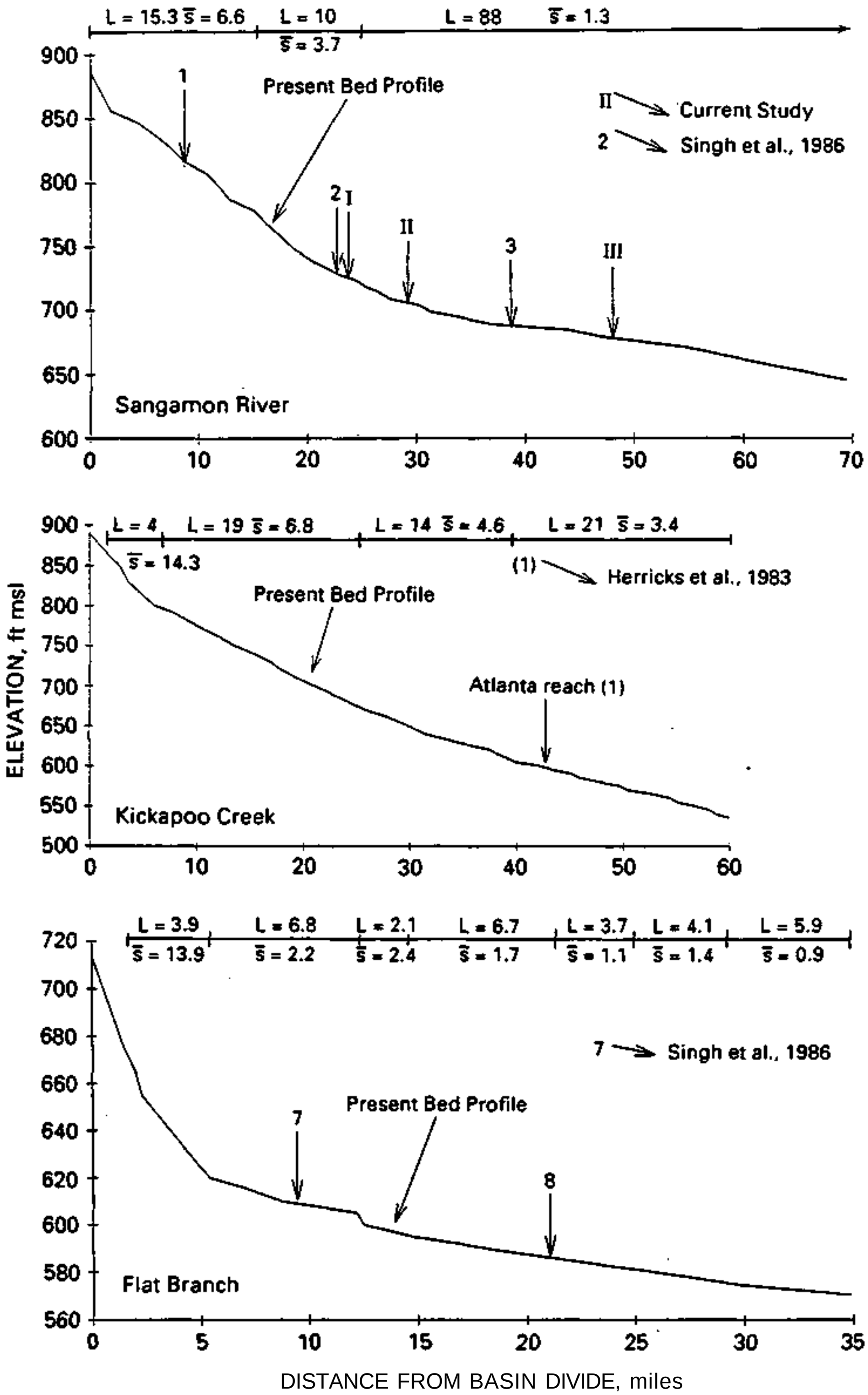


Figure 4. Sangamon River bed profile



Note: $\bar{s}$ = avg. slope, ft/mi
L = length in miles

Figure 5. Streambed profiles for the Upper Sangamon River, Kickapoo Creek, and the Flat Branch

also identified. References to other field studies are given in the legend. Figure 5 shows the bed profile and slopes of the upper portion of the Sangamon River (0 to 70 miles from the basin divide, approximate drainage area 397 sq mi); Kickapoo Creek (tributary to Salt Creek); and the Flat Branch (tributary to the South Fork Sangamon). The Flat Branch has a drainage area of 278 sq mi at its mouth, and the South Fork Sangamon has a drainage area of 132 sq mi above its confluence with the Flat Branch. Kickapoo Creek has a drainage area of 332 sq mi at its confluence with Salt Creek.

The theoretical bed profile and the probable equilibrium bed profile for the Sangamon River Basin were calculated on the basis of the relations and coefficients for the entire Sangamon Basin presented by Stall and Yang (1970) and Yang (1971). The equations defining both the theoretical bed profile and the equilibrium profile were derived by using Strahler's (1957) stream ordering system and Horton's (1945) laws of stream numbers, average stream length, and average stream slope. The theoretical profile represents the average profile of the whole stream system. Differences between the observed profile of a particular stream and the theoretical profile may indicate unusual topographic or geologic features. The equilibrium profile represents the streambed profile of a river where an approximate balance exists between the sediment load and discharge, and it is neither aggrading nor eroding. A river which has reached this condition may be referred to as a mature river. Changes in discharge or sediment load can disturb this balance. Differences between the theoretical or the observed longitudinal streambed profile and the equilibrium profile (determined from Yang's equations) are a measure of the maturity of the stream.

The equation coefficients presented by Stall and Yang for the Sangamon were apparently developed on the basis of data for streams throughout the entire Sangamon River Basin. Because of the geomorphologic differences between the three sub-basins, the coefficients used in the equilibrium profile equations may more appropriately be determined for each basin individually.

The theoretical and equilibrium profiles, the observed bed profile, and the likely profile given the constraint of total fall from the basin divide to the mouth of the Sangamon River are drawn in Figure 4. The theoretical profile lies above the probable equilibrium profile, which indicates that the stream system has not yet reached a state of dynamic equilibrium and will tend to degrade in the future. Several factors may be contributing to the continued adjustment of the basin stream slopes. Extensive alteration of the upland drainage network of the Sangamon Basin has occurred over the last 100 or so years. Marsh and swamp areas have been reclaimed for agricultural and later urban development through the construction of agricultural drainage ditches and field tiles, and storm sewer networks which accelerate drainage. Changes in land use also affect the sediment load of the streams.

The Lake Decatur dam, located approximately 110 miles from the basin divide (drainage area 925 sq mi); was constructed about 1922. A major reservoir was created by the dam, with an estimated 1990 capacity of approximately 18,000 acre-feet. Lake surveys conducted over the years have demonstrated a considerable accumulation of sediment in the lake. The impact of a major reservoir on the river may be seen in reduced bed slope above the dam and increased bed slope below the dam.

The bed slopes along the rivers are shown at the top of the plots in Figures 4 and 5. The length of the stream reach (L) is given in miles, and the average bed slope in the reach (s) is given in feet per mile. The bed slopes reported are for the defined channel as mapped on USGS topographic quadrangles and do not include the fall from the basin divide to the origin of the channel. Overall, Kickapoo Creek has the steepest slopes. The Flat Branch has a considerably less steep bed slope than the other two rivers. Much of the steepness of the upper portion of the Flat Branch is attributable to excavation of an artificial channel to accelerate drainage.

PROGRAM OF FIELD STUDY AND SELECTION OF SITES

The program of field data collection was designed to gather detailed information on the form of riffles and pools in a natural stream setting for drainage areas between 50 and 400 sq mi. Three reaches along the Sangamon River were selected for study. Measured channel characteristics include low flow and bankfull channel widths, and longitudinal variation in bed elevations. The nature of bed materials at riffles and pools, both on the surface and below the surface, was investigated by laboratory analysis of samples collected as well as by in situ measurements. Depths and velocities of flow at three different discharges in each reach were measured to investigate the local variations in these parameters through riffle-pool sequences. Depth, velocity, and bed material information was used to refine the basinwide flow and aquatic habitat model.

The three study sites are located in relatively undisturbed sections of the river so as to represent natural stream conditions for a range of drainage areas less than 400 sq mi. Each reach consists of four consecutive riffles separated by three pools. A study reach begins at the center (relative to the longitudinal or stream wise direction) of the upstream riffle (riffle 1), and ends at the center of the downstream riffle (riffle 4). A systematic procedure was used for measuring various stream characteristics at each site. A grid defined by 19 transects and six points across each transect was established for each reach (see Figure 6). One transect was located at each riffle, and five transects were located in each pool. Transects were equally spaced between riffles. Thus transects 1, 7,13, and 19 are located near the centers of the four identified riffles. The remainder are usually across either a pool or a transition zone. Six uniformly spaced depth and velocity readings were made along each transect. The grid spacing established by the transects and sampling points is in proportion to the stream dimensions: width and riffle-pool spacing. Additional velocity and depth measurements were made at one or more transects for accurate computation of discharge.

Site selection for this study was conducted in 1988 during extreme low-flow conditions. During the fall of 1988, zero flow conditions were frequently observed in the upper reaches of the Sangamon River. The lack of water in the river facilitated identification of coarse material characteristic of riffles. The location and reachwise length of riffles were determined on the basis of bed material observations. Previous field investigations of riffle-pool sequences by the authors were conducted during conditions of considerably higher flows. Riffles, which characteristically are regions of relatively shallow flow, were identified on the basis of observed depth of flow. The

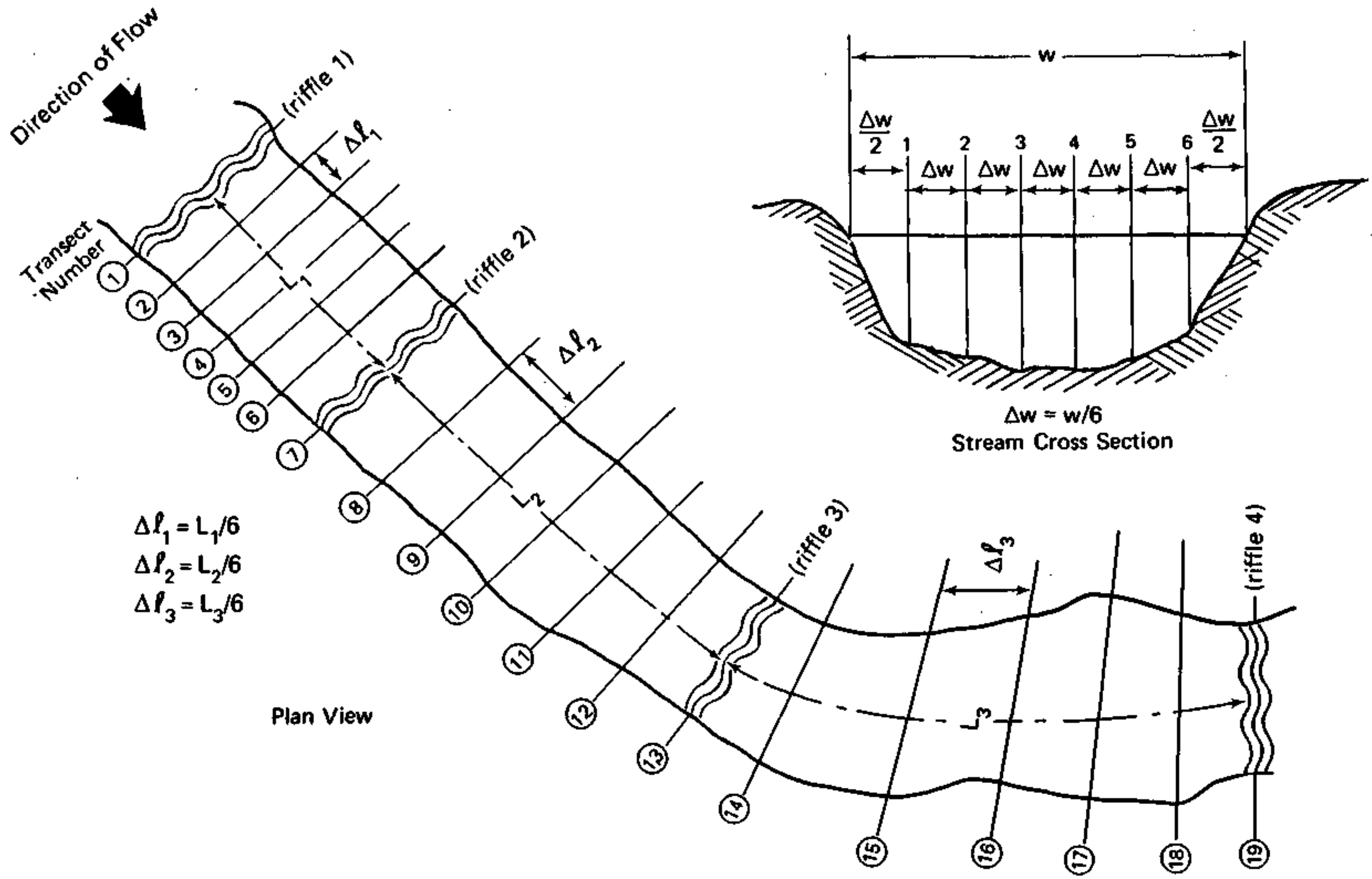


Figure 6. Schematic sketch of transect locations and divisions of channel cross sections

drainage area, river mile, distance from basin divide, reach length, and location of each study reach are given in Table 3. In addition to the study reaches identified for this study, the locations and other pertinent data for stream reaches which have been the subject of previous field studies are also listed in Table 3. Nine reaches along the Sangamon and South Fork Sangamon Rivers were studied by Singh et al. (1986). Four reaches located throughout the entire Sangamon River Basin were studied by Herricks et al. (1983), and three reaches on the lower Sangamon River were studied by Clark et al. (1987).

Channel Characteristics

Channel cross sections and a longitudinal profile of each study reach were surveyed. The apparent bankfull width and low-flow channel width were measured, as well as the lengths of each riffle and pool. The information collected illustrates the channel form and in particular the riffle and pool characteristics of each reach. Comparisons between the reaches are based on non-dimensional parameters as far as possible.

The longitudinal profile of each reach is shown in Figure 7. The elevations shown in Figure 7 are relative to an arbitrary datum set independently at each site; from site to site there is no correlation between the elevations shown. The thalweg elevation is shown by closed circles connected with a solid line. The average cross section elevation is shown by open circles connected with a dashed line. The average elevation was determined from a visual inspection of cross sections plotted by using the survey data.

Generally, the difference between the thalweg elevation and the estimated average bed elevation is less at riffles than at pools. At Site I, there is minor evidence of an incised thalweg at the riffles, and thus a small difference between the average and the thalweg elevations; the difference in elevations at the pools is on the order of 0.5 feet. At Site II, a distinct thalweg cut was observed at most riffles, and this is reflected in the difference between the average and the thalweg elevations plotted for this reach. At Site III, a thalweg cut was observed at some riffles but to a lesser extent than at Site II. At all sites there is on the average a greater difference between the thalweg and average elevations at the pools than at the riffles. Results of channel cross-sectional surveys at each site (Figures 8, 9, and 10) illustrate this observation. The streambed profiles determined from the USGS topographic quadrangles (Figures 4 and 5) show that Site I lies in a river segment having a slope of 0.07 percent (3.7 ft/mi), and Sites II and III lie in a river segment with a slope of 0.025 percent (1.3 ft/mi). The expected fall along the distance from transect 1 to transect 19 at Sites I, II, and III was

Table 3. Study Reaches

Reach no.	*Drainage area (sqmi)*	*River mile**	*Distance from basin divide (mi)*	*Reach length (ft)*	*Section, township, and range*
Sangamon River					
I(1)	55.5	219	22.3	426.0	S06T22NR7E
II(1)	114.6	212.4	28.9	924.0	S11T22NR7E
III(l)	291.5	193.1	48.2	1,508.8	S26T21NR7E
1(2)	19.1	232.7	8.6	329.0	S27T23NR5E
2(2)	55.8	220.0	21.3	166.0	S06T22NR7E
3(2)	240.0	201.5	39.8	860.0	S06T21NR8E
4(2)	613.0	151.4	89.9	1,200.0	S30T18NR5E
5(2)	1,439.0	87.9	153.4	825.0	S25T16NR4W
Monticello(3)	575	158(5)	83.3	1,867.0(6)	T18NR05E(5)
Athens(3)	3,008	53(5)	188.3	2,667.0(6)	T18NR06W(5)
Riverton(4)	2,621.5	83.1	158.2	910**	S05T16NR04W
Salisbury(4)	2,906.3	62.0	179.3	1,052**	S27T17NR06W
Petersburg(4)	3,062.5	47.5	193.8	1,195**	S12T18NR07W
Kickapoo Creek					
Atlanta(3)	270	19.1(5)	42.9	1973(6)	S04 T20N R01W(5)
A	70**	44.4	17.6	330	S23T22NR02E
B	140**	32.4	29.6	483	S11T21NR01E
C	235**	24.0	38.0	442	S25T21NR01W
Long Point Creek					
D	50**	0.2	17.2	170	S15T21NR01E
South Fork Sangamon					
6(2)	13.4	81.2	5.6	550.0	S36T11NR02W
9(2)	715.0	16.2	70.6	1,183.0	S03T14NR04W
Kincaid(3)	607.0	32.0(5)	54.8	1,178.2(6)	S27 T14N R03W(5)

Table 3. Concluded

Reach no.	Drainage area (sqmi)	River mile*	Distance from basin divide (mi)	Reach length (ft)	Section, township, and range
Flat Branch					
7(2)	77.3	27.8	9.0	165.0	S22T13NR02E
8(2)	190.5	15.4	21.4	570.0	S34T14NR01E

Notes:
* distance measured from confluence with the Illinois River (from Healy, 1979)
** estimated
(1) present study
(2) Singh et al., 1986
(3) Herricks et aL, 1983
(4) Clark et al., 1987
(5) located on the basis of drainage area given
(6) estimated from scaled drawings in final report

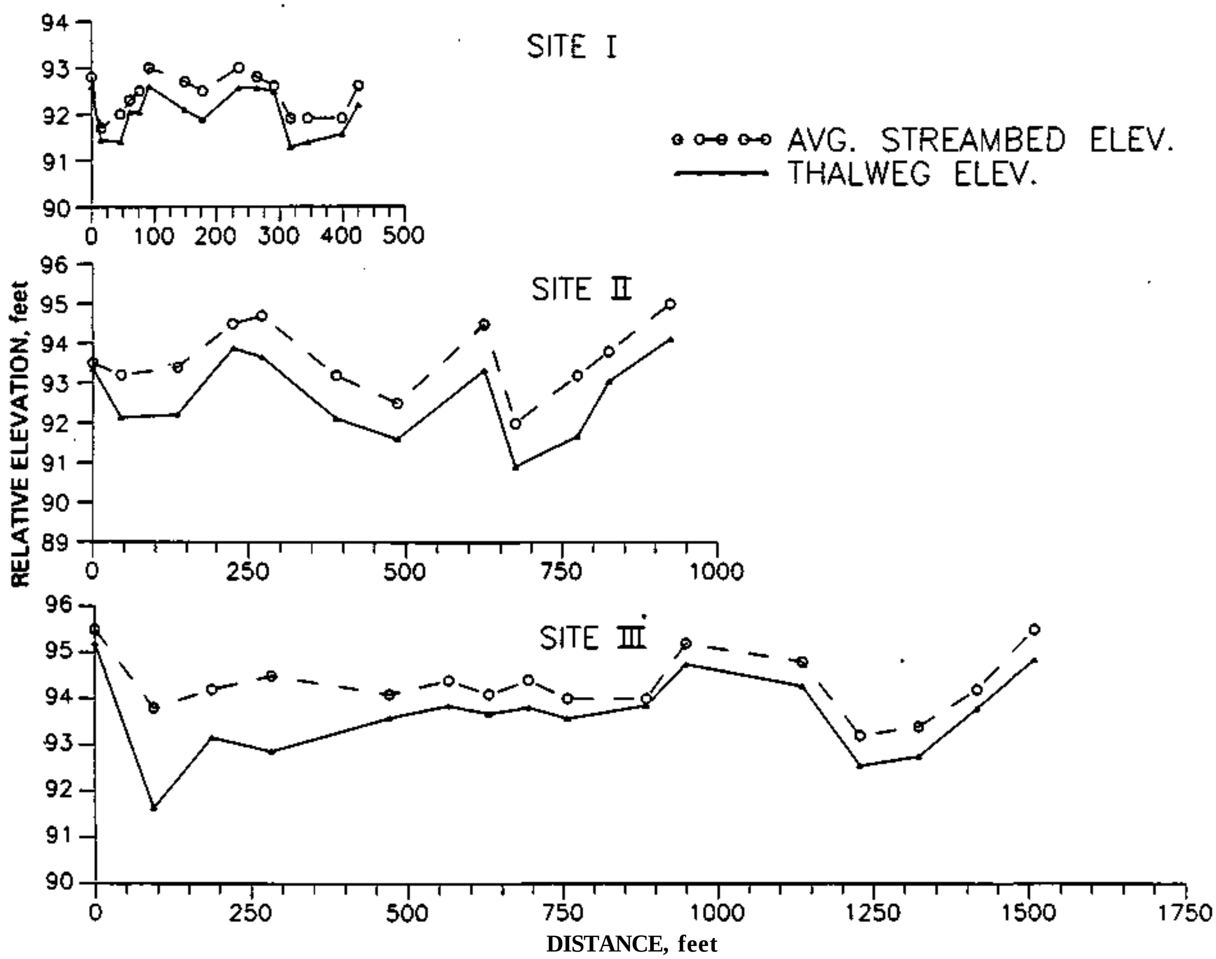


Figure 7. Longitudinal profiles of study reaches

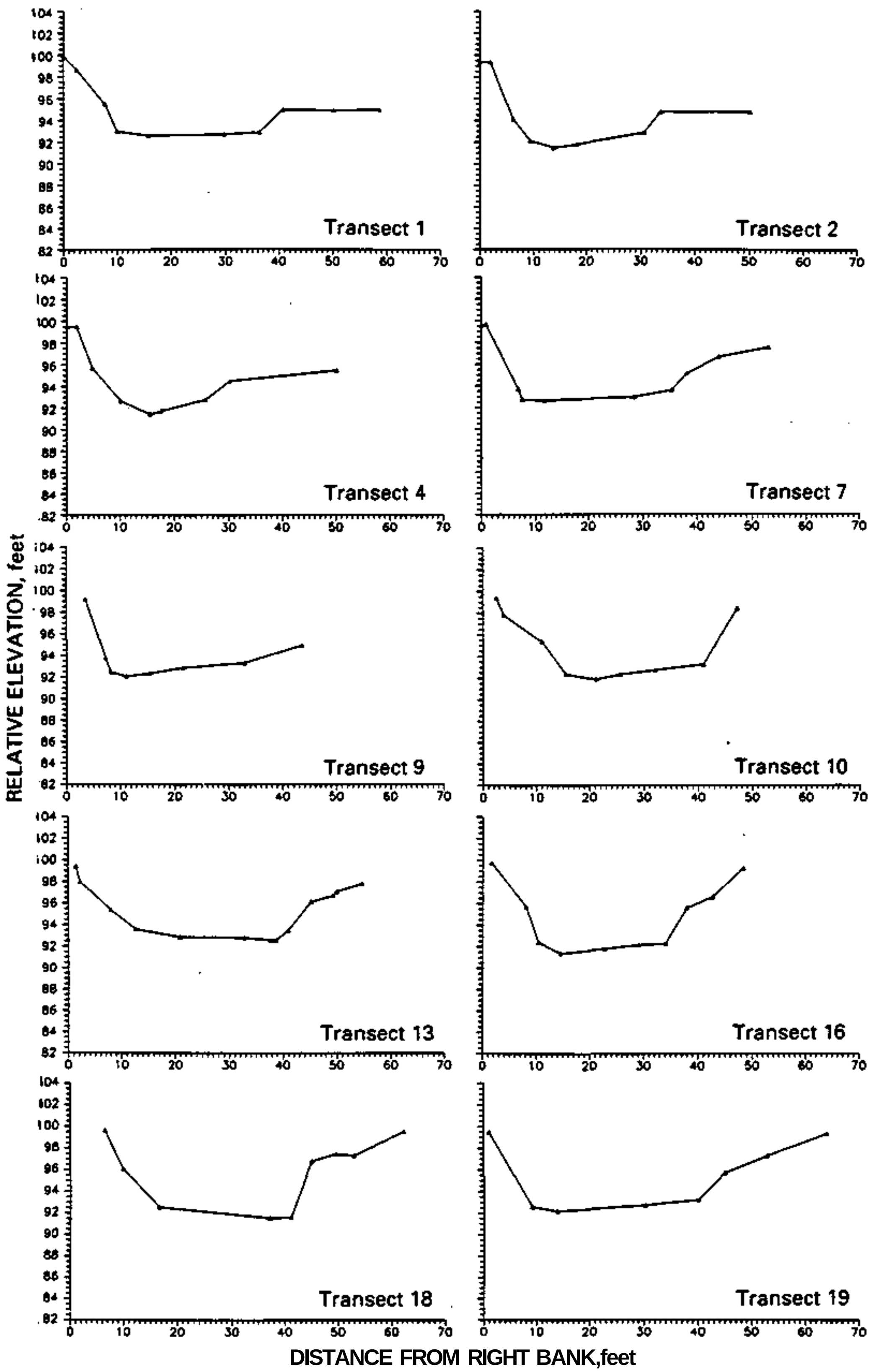


Figure 8. Cross sections surveyed at Site I

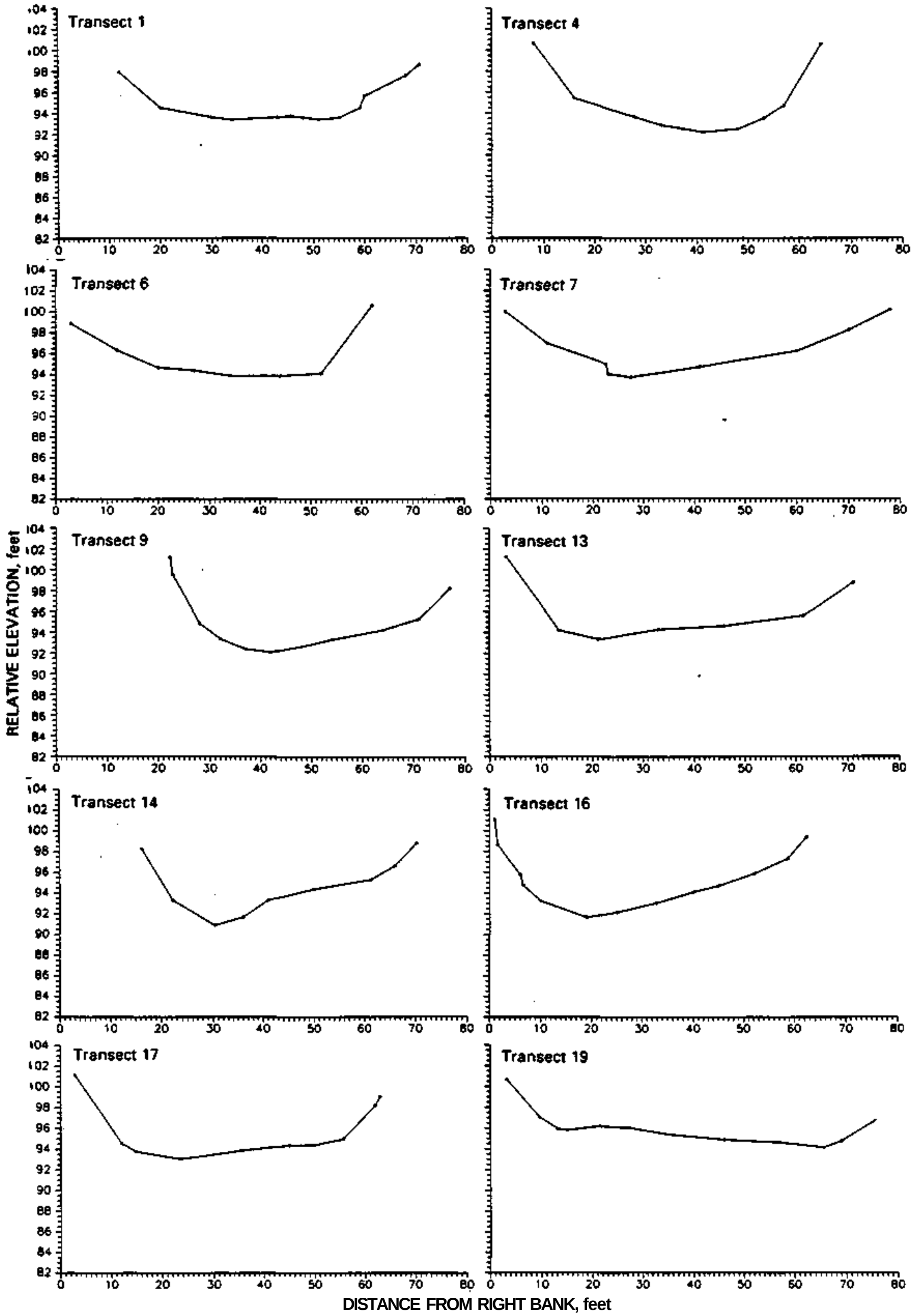


Figure 9. Cross sections surveyed at Site II

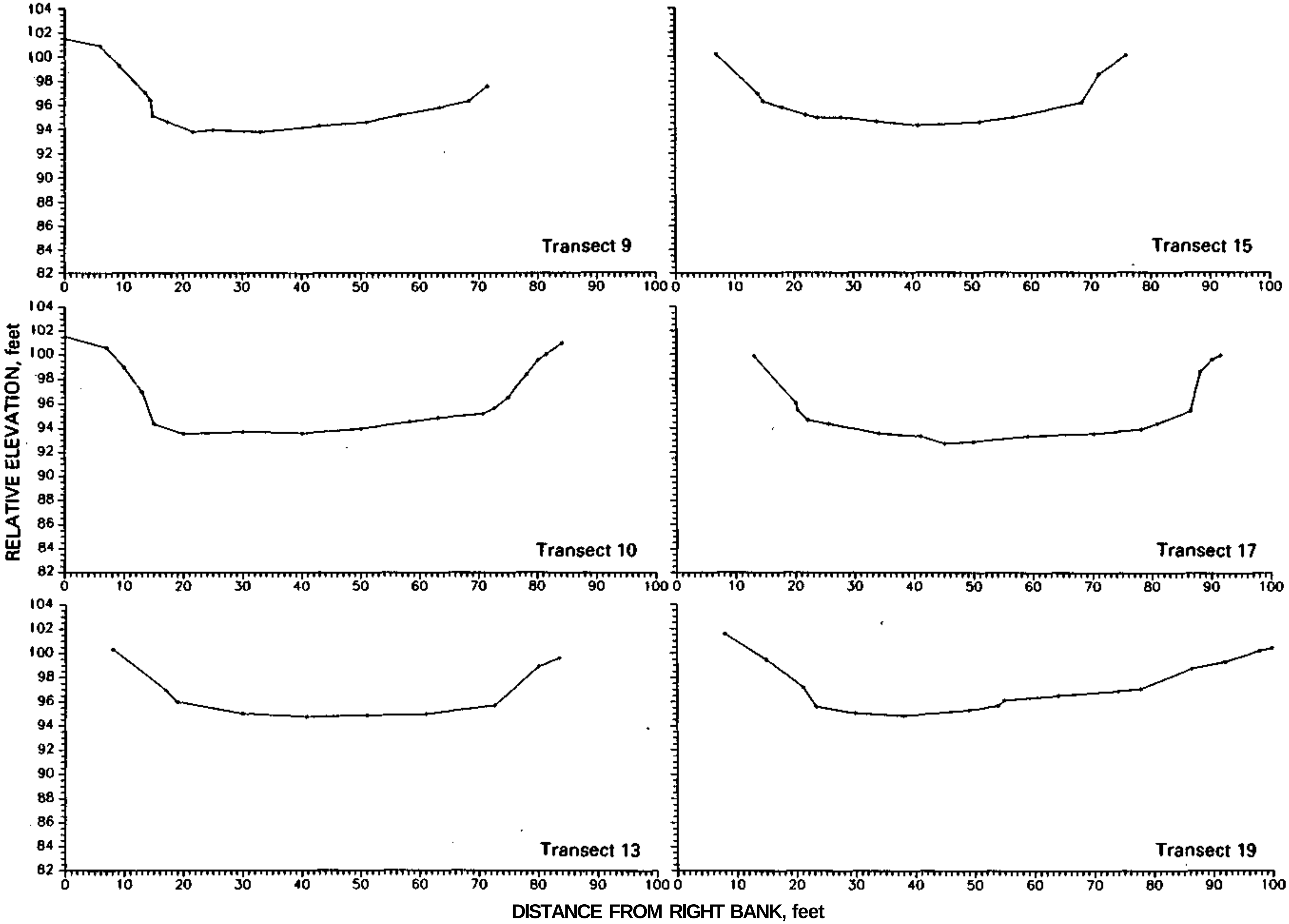


Figure 10. Cross sections surveyed at Site III

computed on the basis that these slopes are 0.3, 0.23, and 0.38 ft, respectively. The difference in thalweg elevations from transect 1 to transect 19 is 0.4 ft at Site I and 0.36 ft at Site III, which is in close agreement with the computed fall. At Site II the elevation of transect 19 is higher than that at transect 1. This is believed to be a by-product of channel excavations downstream.

Local slopes from riffle to pool and pool to riffle (determined from the average cross-section elevation) of surveyed transects are considerably steeper than the overall bed slope. These transect-to-transect slopes at Site I are greater than at Sites II and III, as is the overall slope. Inspection of Figure 7 shows the relative steepness of the transition zones from riffle to pool and pool to riffle, with comparatively flat segments in the center portions of pools and at the longer riffles (where more than one transect lies on the riffle). Transition zone slopes at Site I are typically greater than 2 percent (range: 0.9 to 7 percent); at Sites II and III they are typically on the order of 1.5 percent (range: 1.2 to 1.8 percent). In the relatively flat portions of pools, slopes between measured transects range from 0 to about 0.9 percent (typically around 0.7 percent at Site I and 0.5 percent at Sites II and III).

Bankfull width, W_b, was determined from the cross-sectional plots. On the basis of these cross sections the width-to-depth ratio, W_b/D, was computed for each cross section. The average W_b and W_b/D ratio was computed for riffles (transects 1, 7, 13, and 19), and the average W/D ratio was computed for pools (transects 2 through 6, 8 through 12, and 14 through 18). These values are shown in Table 4. The W_b at riffles at each site is, on the average, larger than at pools. The W_b/D at riffles is larger than at pools for all three sites, and increases in the downstream direction. The increase in W_b/D with drainage area is predicted by substituting hydraulic geometry equations for W and D. Assuming that bankfull discharge has a return interval of 1.8 years (Dunne and Leopold, 1978), the product obtained by multiplying the hydraulic geometry coefficients b and d by the decimal flow duration F will be negligible. Thus using the hydraulic geometry equations for high flows, $\log (W_b/D) = 0.976 + 0.115 (\log DA)$. The W_b/D ratios calculated from this equation are 15.0,16.3, and 18.2 for Sites I, II, and III, respectively.

The stream wise lengths of riffles and pools at approximately the centerline of the channel were measured in each reach. Riffles were identified on the basis of visible bed materials as previously described. The measured lengths of riffles and pools are given in Table 5. The entire lengths of the upstream and downstream riffles were measured. However, the total reach length noted in the table extends only from transect 1 to

Table 4. Bankfull Widths and Width-to-Depth Ratios at Study Sites

	Riffles				Pools				Reach Avg.	Hydraulic geometry predicted
Site	W_b	S_w	W_b/D	S_r	W_b	S_w	W_b/D	S_r	W_b	*W/D*
I	36	3.7	12.4	0.9	34.3	4.7	10.4	2.1	35	15.0
II	63.3	5.0	15.4	2.3	54.1	2.9	10.4	1.1	56	16.3
III	67.8	3.9	17.4	3.1	65.5	4.7	13.1	0.9	66	18.2

Notes:

All values are in feet
W_b = bankfull width
S_w = standard deviation of measured bankfull widths
D = average depth at a transect, from top of bank elevation to average bottom elevation
S_r = standard deviation of W_b/D ratio

Table 5. Riffle and Pool Lengths

	Sangamon Basin			*Salt Creek Basin*			
	Site I	*Site II*	*Site III*	*A*	*B*	C	D)
Drainage area, sq mi	55.5	114.6	291.5	70	140	235	50
Reach length (1)	426	924	1508.8	330	483	442	170
Riffle 1, transect 1 (2)	17.1	35.9	152.0	245	105	133	118
Pool 1	66.8	209.5	460.0	137	336	234	112
Riffle 2, transect 7	33.0	78.5	123.0	178	117.5	180	79
Pool 2	119.1	297.4	255.0		.	. .	.
Riffle 3, transect 13	84.3	52.6	239.0	-	-		
Pool 3	99.7	211.0	288.0	-	-	-	-
Riffle 4 , transect 1 9 (2)	49.9	136.0	148.0		.	. .	.
Avg. riffle length, R	46.1	75.8	165.5	211.5	111.3	156.5	98.5
Avg. pool length, P	95.2	239.3	334.3	137	336	234	112
P/R	2.07	3.16	2.02	0.65	3.02	1.50	1.14
% Reach-riffle (3)	33%	22%	34%	58%	30%	47%	34%
% Reach-pool (4)	67%	78%	66%	42%	70%	53%	66%
RR	142	308	503	330	483	442	185
W_{20}	24.8	37.5	64.0	31.2	45.8	61.7	25.8
RR/W_{20}	5.7	8.2	7.9	10.6	10.5	7.2	7.2
RR/W_b	4.1	5.5	7.6				
Slope, ft/mi (5)	3.7	1.3	1.3	6.8	4.6	4.6	

Notes:
All distances in feet unless otherwise noted
(1) distance from center of riffle 1 (transect 1) to center of last riffle (transect 19 or 7)
(2) total observed riffle length; includes portion beyond boundaries defining study reach length
(3) sum of riffle lengths within boundaries of study reach divided by reach length
(4) sum of pool lengths divided by reach length
(5) average slope determined from Figure 5
RR average riffle-to-riffle spacing
W_{20} width corresponding to 20% flow duration discharge calculated from hydraulic geometry equations
W_b bankfull width

transect 19, in other words from the center of the first upstream riffle to the center of the last downstream riffle.

Both riffle and pool length increase with drainage area. However, relative to stream length, the proportions of riffles and pools in the Sangamon reaches remain fairly constant. About 30 percent of the reach length is riffle, with the remainder in transition zones and pools. Also shown in Table 5 are riffle and pool lengths measured at four sites in the Salt Creek Basin (sites A, B, C, D). Although beyond the scope of the current project, these four sites were visited and measurements were made to take advantage of the extreme low-flow conditions occurring during the summer and fall of 1988. At three of the four sites, riffles occupied a lesser proportion of the stream length than pools. As only one pool was measured, these data may not be as representative as the data from the Sangamon Basin, but they do indicate the same general proportions of riffle and pool areas.

Along the stream length, average riffle-to-riffle spacing is typically 5 to 7 times the channel width (Leopold and Maddock, 1953; Harvey, 1975). The spacing between riffles has been shown to correlate closely with average flow widths calculated from hydraulic geometry relations for the 20 percent flow duration discharge (Harvey, 1975). The ratio of average riffle-to-riffle spacing (RR) and calculated width (W_{20}) corresponding to a 20 percent flow duration discharge were computed for the study reaches and are listed in Table 5. All but one RR/W_{20} ratio is greater than 7. The ratio of RR to W_b (average bankfull width, Table 4), also shown in Table 5, is less than RR/W_{20} at each reach and is closer to the typical value range of 5 to 7.

The relationship between logarithms of riffle spacing and channel width is linear. A logarithmic plot of riffle spacing versus width was developed from the combined data for study reaches in the Sangamon, South Fork Sangamon, and Salt Creek Basins, as shown in Figure 11. Sangamon Basin sites include Sites I, II, and III from the current project, as well as sites identified as 1, 2, 3, 4, and 5 on the Sangamon River (Singh et al., 1986). South Fork Sangamon Basin sites on the Flat Branch and South Fork Sangamon Rivers are identified as 6, 7, 8, and 9 (Singh et al., 1986). Salt Creek Basin sites A, B, C, and D on Kickapoo Creek and Long Point Creek were studied as part of the current project (see Table 3). A straight line was fit by eye to the data points. Reaches 1 and 6 are believed to have been channelized, and thus have greater spacing between riffles. The riffle-to-riffle spacing tends to be lower for sites in the South Fork Sangamon Basin than for the Sangamon and Salt Creek Basins.

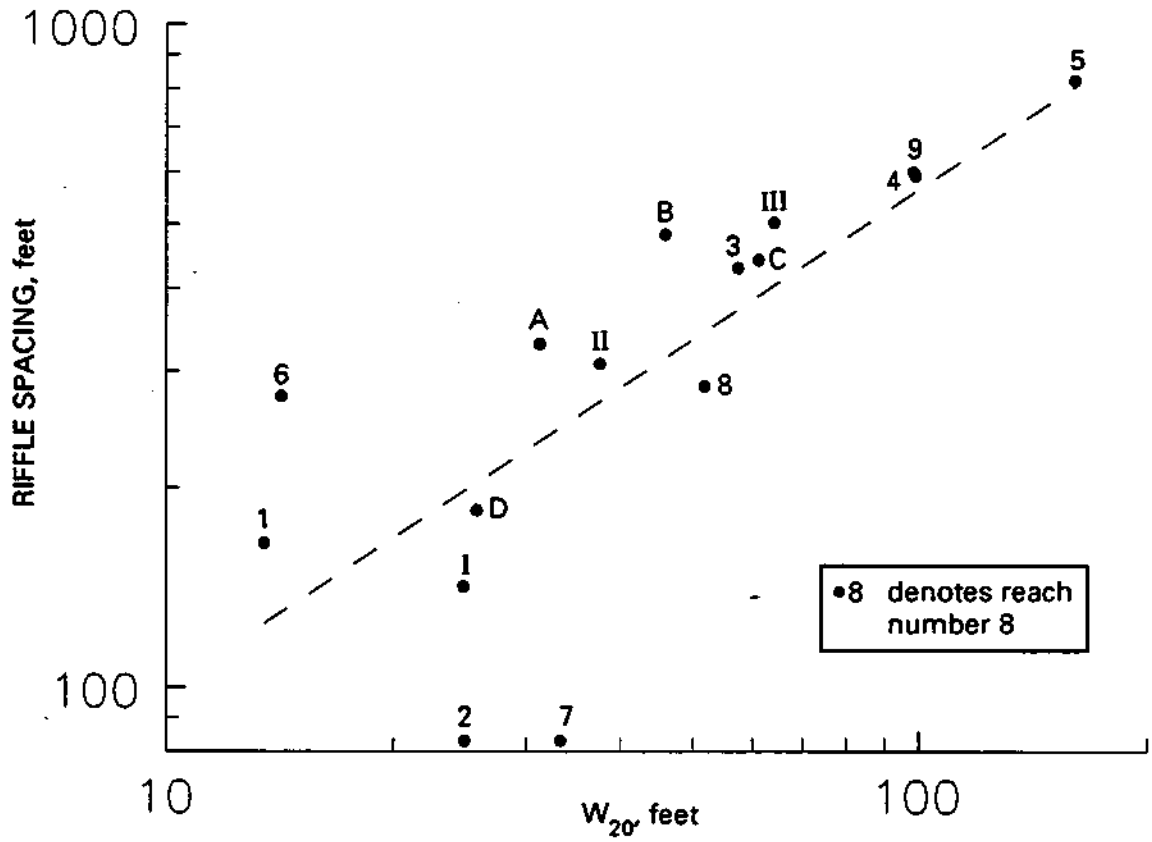


Figure 11. Riffle spacing versus width corresponding to a 20% flow duration discharge (W_{20})

BED MATERIALS

Bed materials, both on the surface and below the surface, were inspected in all three study reaches. A visual inspection of bed material at three locations on Kickapoo Creek in the Salt Creek Basin was also conducted for comparison. The program of bed material inspection, sampling, measurement, and analysis was designed to meet several objectives. Surface materials are an intrinsic component contributing to the quality of the stream aquatic habitat. Bed materials vary from riffle to pool and also differ along a stream network. A means of predicting expected bed materials for streams throughout the basin network is needed to more completely define the aquatic habitat in the basinwide flow and aquatic habitat assessment model. Information on the typical composition of bed materials of natural riffles can be applied to stream restoration efforts involving the reestablishment of riffle-pool sequences in channelized streams.

The study of bed materials was expanded beyond simple classification of surface material to explore the vertical structure of natural riffle and pool sequences in the study reaches. The data collected provide basic information on the form of riffles and pools. Subsurface sampling, visual inspection, and penetrometer probing were conducted to determine the density of bed materials and to classify the soil types. Grain size classifications jointly adopted by the American Society for Testing and Materials and the American Society of Civil Engineers (ASTM-ASCE) are shown in Table 6. Familiar examples are given to indicate relative sizes and to define descriptive terms such as fine gravel and medium sand. Four sequential riffles define each study reach, and transects 1, 7, 13, and 19 cross at approximately the center of each of these riffles (Figure 6). Transect 1 is at the upstream end of the study reach

Table 6. Grain Size Identification (Sowers, 1979)

	Size limits	*Familiar example*
Boulder	12 in. (305 mm) or more	Larger than basketball
Cobbles	3 in. (76 mm)-12 in. (305 mm)	Grapefruit
Coarse gravel	3/4 in. (19 mm)-3 in. (76 mm)	Orange or lemon
Fine gravel	4.75 mm (No. 4 sieve)-3/4 in. (19 mm)	Grape or pea
Coarse sand	2 mm (No. 10 sieve)-4.75 mm (No. 4 sieve)	Rocksalt
Medium sand	0.42 mm (No. 40 sieve)-2 mm (No. 10 sieve)	Sugar, table salt
Fine sand*	0.075 mm (No. 200 sieve)-0.42 mm (No. 40 sieve)	Powdered sugar
Fines	Less than 0.075 mm (No. 200 sieve)	

*Particles finer than sand cannot be discerned with the naked eye at a distance of 8 in. (20 cm).

and transect 19 at the downstream end of the study reach. For clarity and ease of discussion, the four riffles in each study reach are identified by the transect numbers 1, **7,13,** and **19.**

Visual Inspection and Description of Sites

Data collection began in September 1988. The severe drought conditions occurring at that time were clearly evident in the low streamflow observed in the Sangamon River. New low-flow records were established at gaging stations on the river. When the sites were visited in September, October, and the first part of November there was virtually no flow. On most occasions, no water was visible at the riffles and only standing water was visible in the pools. These conditions provided an opportunity for visual inspection of the bed materials at the riffles. A thick layer of organic silt was found in the pools at Sites II and III. While organic silt deposits are not atypical of pools, the thickness of the deposit may in part be attributable to the ponding of the water. The ability to see the riffle material clearly was a great benefit to the design of the sampling program. The bed materials observed in each reach are described below.

Site I

Surface materials observed at this site were comparable from riffle to riffle, as was the appearance of pool materials. Riffle material is a mixture of predominantly coarse to fine gravel and coarse sand, covering the riffle areas fairly uniformly from bank to bank. Some scattered cobbles having nominal diameters of 3 to 8 inches (76 to 204 mm) were observed at this site on the riffles. Very little organic silt "muck" was found in the pools, which typically had fine to medium sand, similar to the finer fraction of the soil mixture found at the riffles. Subsurface exploration revealed clay a few inches below the surface at both the riffles and pools.

Site II

At this site, riffle bed material varied from fine and coarse gravel at the upstream riffle to coarse sand at the riffle farthest downstream in the study reach. The central portion of the farthest upstream riffle (transect 1) was fairly uniformly covered with fine to coarse gravel. Silty sand was deposited near the banks. Bed material at the next two riffles (transects 7 and 13) was a mixture of fine gravel and coarse sand that extended over about two-thirds of the cross section. Silty sand was found in the low-flow channel cut along the bank and through the riffle. Cross sections of these riffles show a well-developed thalweg cutting through the riffle along the bank, forming a low-flow channel. The low-flow channel extends about one-third of the way across the main channel section; the thalweg is about one foot lower than the average bottom elevation at the cross section. Bed material at the riffle farthest downstream (transect 19) is primarily medium sand with some coarse sand, covering the transect from bank to bank fairly uniformly. Cobble-size material was absent at this site. Pools had a deep layer of organic silt having a depth of several feet in some areas. Medium sand was observed in portions of pools not covered with the organic silt, typically near the bank, and in transition zones between riffles and pools.

Approximately 300 feet downstream of the last riffle (transect 19), a broad expanse of sand extending downstream about 400 feet was observed. Elevations taken at three cross sections along this sandy deposit reveal that the elevation of this portion of the stream is higher than that of the four riffles defining the study reach. A bridge crosses the stream about 700 feet downstream of transect 19. Periodically, accumulated sediment around bridges is cleared out to maintain an adequate channel cross section to pass floods. On the basis of the appearance of the stream channel between transect 19 and the bridge and observation of channel clearing procedures around bridges, the deposit of sand was likely created artificially as a by-product of maintaining the channel opening at the bridge. This feature influences the upstream flow characteristics and likely the sediment deposits in the study reach.

Site III

Two riffles at this site (transects 1 and 19) were fairly uniformly covered with coarse sand and fine gravel from bank to bank. Bed material at the other two riffles (transects 7 and 13) varied from bank to bank, with medium sand, coarse gravel, and cobbles across one-half to two-thirds the riffle width, and medium sand on the remaining portion. Cobbles observed around transects 7 and 13 had nominal diameters from 3 to 6 inches (76 to 152 mm). The cobbles were, on the average, smaller than observed at Site I but larger than any material observed at Site II. The riffle crossed by transect 7 is not well developed. This site was identified as a riffle on the basis of coarse material observed at this location and its position relative to the other riffles. The longitudinal profile of the reach developed from the survey information shows that the elevation of this riffle is less than that of the next downstream riffle. This riffle may be migrating. The central portions of the pools in this reach were characterized by deposits of organic silt similar to the material observed at Site II, but deeper at many locations. Riffle-to-pool transition zones were identifiable, having less coarse material than found at the riffles but without the organic silt layer observed in pools. Bed material samples taken in these zones serve as an indicator of bed material below the layer of organic silt in the pools. The excessive silt depths in the pools were caused to some extent by stagnant waters during conditions when there was practically no flow.

Observations along Kickapoo Creek

Surface materials were visually inspected and penetrometer tests were conducted at four locations on Kickapoo Creek, a tributary of Salt Creek in the Sangamon Basin. Drainage areas ranged from 70 to 235 sq mi. In most cases only one riffle-pool-riffle sequence was examined at each site. All measurements were taken at transects defining the center of the riffle or pool. Observations were recorded in the field and samples were collected and were later examined in the office.

Samples were collected with a scoop from the top 3 inches of the bed. Most transects were covered with uniform material; when differences were noted, composite samples were collected, including all types of materials observed. Two samples were collected at each riffle and pool; the one identified as most representative was qualitatively classified. Riffle material became coarser at each successive downstream site, varying from coarse sand and fine gravel at the farthest upstream location to coarse gravel and cobbles at the farthest downstream location. Material in all examined pools was silt and fine sand, with small fractions of coarser material. This was the same general pattern observed at the three study sites on the Sangamon River.

Penetrometer readings were taken at six equally spaced points across each riffle and pool transect. In general, higher readings (and shallower depth penetrations) were attained at riffle transects, and lower readings (and greater depth penetrations) were attained at pool transects. For the pool locations, the average depth to the firm bed was 2 feet below the surface; observed depths ranged from 1 inch to 4 feet.

Sampling Program

At riffles, samples were collected for laboratory analysis, and on-site assessments of surface bed material were conducted. In the remaining portions of the reaches, only sample collections for laboratory analysis were conducted. Standard numerical parameters used to describe soils are D_{50} (the median particle diameter) and D_{90} (the particle diameter at which 90 percent of the material is finer by weight and 10 percent is coarser). Other descriptive nominal diameters such as D_{20} are similarly defined. The gradation of a soil is an indicator of the range of particle sizes present. A well-graded soil will have a continuous spectrum of particle sizes from the smallest to the largest particles. A uniformly graded soil has a narrow range of particle diameters. When an intermediate range of particle diameters is not present, the material is described as gap-graded. The traditional method for determining these values relies on developing plots using the results of sieve analysis for coarse-grained material (D > 0.74 mm) and pipet or sedigraph analysis of fines, silt, and clay (D <0.74 mm). A second method employed was proposed by Wolman (1954) specifically for classification of bed materials in streams and rivers. The two procedures are described below and the results compared.

Surface bed materials were collected in riffles and in pools in all three reaches. Laboratory sieve and sedigraph analyses were performed to determine the weight distribution of grain sizes. Grain-size curves were developed for each sample by plotting the grain size D in mm versus P (the percent weight of finer materials) on semi-logarithmic paper. Grain size corresponding to selected percent weight (P) values such as 50 or 90 are read from the logarithmic scale. The gradation of the samples was determined from the curvature of the grain size charts. To a greater or lesser extent, nearly all of the surface samples analyzed exhibited the curvature inversion characteristic of gap-graded soils. However, in many cases, the departure of the curve from the classic well-graded form was slight and the materials were classified as well-graded.

The procedure proposed by Wolman (1954) defines the distribution of grain sizes on the basis of the frequency of occurrence of nominal particle diameter as found at the site. A grid of 100 or more points is established in the desired area of a reach, such as a riffle. Three intermediate diameters of the particle at each grid point are measured. Average particle diameter is calculated for sampled grains. A grain-size distribution curve is developed by plotting the cumulative probability distribution of average diameter of particles. Fine-grained particles, less than a few millimeters, cannot be measured and are grouped together as fines, D<~2mm. This sampling was performed in two riffles at each reach.

Between 14 and 17 samples were taken at each site for laboratory analysis. Surface samples, approximately the top 3 inches, were collected with a scoop. Subsurface samples (the top 8 to 12 inches) were obtained with a Shelby tube sampler. Samples were inspected and compared in the office. Samples with similar makeup were identified and only one analyzed for grain size. This procedure minimized duplication of information derived from the laboratory grain size analysis and thus maximized the variety of samples analyzed within budget constraints. For example, organic silt was observed over much of the pool area at Sites II and HI. Samples were collected at several pools at both sites. Inspection of the samples showed them to be essentially the same, and only one was selected for laboratory analysis. In a few cases, the sample taken with the Shelby tube was essentially the same as the surface sample, and only one was selected for analysis. Because of the channel disturbance downstream from Site II, this reach may not be as representative of natural conditions as the other sites. Therefore fewer samples for this reach were analyzed, allowing for more detailed data collection at the other two sites.

As noted in the visual descriptions of Sites II and III, the bed material varied from bank to bank at some riffles, ranging from coarse to relatively fine materials. Some separate samples were taken of the coarse materials and the fine materials, and some composite samples were also taken over the whole cross section. When two samples were taken (of the coarse and fine material across the section), the weighted distributions provided by laboratory analysis were mathematically combined to provide composite values of selected particle diameters. These values were then compared to those for composite samples taken in the field.

It was difficult or impossible to retrieve subsurface samples of the firm bottom at deeper, central portions of pools at Sites II and III because of the depth of the organic silt. Samples were taken at cross sections that may be described as transition zones. These sections of the reaches are not as deep as the pools. However, they do not have the coarse bed material observed at the riffles and may be indicative of the firm bed material below the silt in the pools.

Grain Size Analysis Results and Discussion

Results of the individual sample grain size analyses are presented in Tables 7, 8, and 9. A summary of the data is given in Table 10. Representative values for the riffle and pool bed materials are presented in the summary table. These values do not represent averages of the individual samples; factors such as similarity to other samples collected but not analyzed and observations of subsurface materials were taken into consideration.

The results of the grain size analysis of material collected at riffles is shown in Table 7. At Site I, riffle material was fairly uniformly and consistently distributed, which is demonstrated by the consistency of the results for both the laboratory analyses and on-site measurements. At Site II, the coarser material that covered about two-thirds of the riffle at transects 7 and 13 was similar to material observed at the first upstream riffle, transect 1. However, a greater proportion of coarse gravel was

Table 7. Riffle Surface Bed Materials

Trans. no.	*Laboratory analysis of samples* D_{50}	D_{90}	D_{20}	*Gradation*	*On-site measurement of particle diameter* D_{50}	D_{90}	D_{20}	*Gradation*
Site I								
1	2.5	55	.013	well				
7	5.0	19	.35	gap				
13	4.5	18	.35	well	18.0	43	3.3	weathered uniform
19					16.0	56	.24	weathered uniform
Site II								
7(1)	2.5	16	.22	well	2.0	27	.33	gap
13(1)	1.2	15	.053	well	1.9(1)	29	.27	gap
13(2)	7.0	19	.69	well	10(2)	37	.64	gap
13(3)	.13	2	.006	well				
Site III								
1	1.2	10.7	.39	well	12.5	22.5	2.8	gap
13(1)*	8.3	38	.33	gap	3.5	61.0	.26	gap
13(2)*	15.0	45	.67	well				
13(3)*	.4	.95	.27	uniform				
15(1)*	1.25	60	.31	gap				
15(2)*	12.5	90	.31	gap				
15(3)*	.5	1.2	.30	gap				
19	4.4	11	.51	well				

Notes:
All grain size values in millimeters

(1) Composite sample of surface bed material which varied across the stream cross section (bank to bank).
(2) Bed material varies across section, results for sample of coarser material which covers about two-thirds of channel width.
(3) Bed material varies across section, results for sample of finer material only

*At Site HI, transects 13 and 15 cross the same riffle, transect 13 is near the center of the riffle, transect 15 is close to transition zone; similar material found at transect 7 in the reach

Table 8. Riffle Subsurface Materials

Trans. no.	*D_{50}*	*D_{90}*	*D_{20}*	*Gradation*	*Comments*
Site I					
1	**.014**	**1.5**	**.001**	**well**	**top 12.4"**
7	**.016**	**.47**	**.001**	**well**	**top 9.9"**
Site II					
19	**.44**	2.2	**.17**	weathered uniform	top 14.9", riffle may be a by-product of bridge clearing

Observation Pit

Trans. 7	*Depth*	*Soil observation*
Top 3" **D_{50} = 2.5** **D_{90} = 16** **D_{20} = .22**	**0"–3"**	**coarse sand and coarse gravel**
	3"–5"	**fine gravel, medium sand, silt, and clay**
	5"–10"	**fine gravel, medium to fine sand, silt, and clay**
	10"–17"	**fine gravel, medium to coarse sand**

Trans. 13	*Depth*	*Soil observation*
Top 3" **D_{50} = 1.2** **D_{90} = 15** **D_{20} = .053**	**0"–3"**	**coarse sand and fine gravel**
	3"–14"	**fine gravel in a coarse sand & clayey silt matrix**
	14"–17"	**fine gravel in a coarse sand & clayey silt matrix**

Note: All grain size values in millimeters

Table 8. Concluded

Site III

Observation Pit

Trans. 1	*Depth*	*Soil observation*
Top 3" D_{50} = 1.2 D_{90} = 10.7 D_{20} = .39	0" – 9"	coarse sand and fine gravel
	9" – 17"	coarse sand (no gravel)
	17" – 20"	coarse sand and fine gravel

Trans. 13	*Depth*	*Soil observation*
Top 3" D_{50} = .4 D_{90} = .95 D_{20} = .27	0" – 8"	medium to coarse sand
Top 8.4" D_{50} = .5 D_{90} = 1.5 D_{20} = .2	8" – 10"	fine gravel in a coarse sand & clayey silt matrix

Note: All grain size values in millimeters

Table 9. Pool and Transition Zone Bed Materials

Trans. no.	D_{50}	D_{90}	D_{20}	*Gradation*	*Comments*
Site I					
4	.33	**8**	.007	gap	top **11.5",** central portion of pool
10	.42	1.3	.27	uniform	top 3", central portion of pool
10	.055	2	.001	gap	top 13.9", central portion of pool, clay
15	1.0	10.4	.26	gap	top 3", transition zone
Site II					
10	**.2**	.85	**.006**	gap	top **8.9",** comparable to surface samples collected at transects 4 and 10
16	.01	.11	.001	gap	sample of organic silt observed in pools at Sites II and III, 3-foot depth in some locations
Site III					
6	**.61**	**1.8**	.38	uniform	top 10.1", comparable to surface samples at same location
9	.24	21	.006	gap	top 9.6", pool
15	.50	1.2	.30	uniform	top 3", transition zone
15	.30	.9	.17	uniform	top 12.9", transition zone
Pool	.01	.11	.001	gap	results of analysis of organic silt found in central portions of pools at Sites II and III, only one sample analyzed, over 1 foot depth in some locations.

Note: All grain size values in millimeters

Table 10. Summary of Typical Grain Sizes Determined from Laboratory Analysis of Bed Materials

Site	River mile*	Drainage area		Surface (top 3") Riffle	Surface (top 3") Pool	Surface (top 3") Transition	Sub-surface (top 8 to 12") Riffle	Sub-surface (top 8 to 12") Pool	Sub-surface (top 8 to 12") Transition
I	219	55.5	D_{50}	4.0	.38	1.0	.015	.055	.33
			D_{90}	31	4.7	10.4	.99	2.0	8.0
			D_{20}	.24	.14	.26	.001	.001	.007
II	212	114.6	D_{50}	2.5	.01(1)	.2	1.2(2)	.01(1)	.2
			D_{90}	16	.11(1)	.85	15.0(2)	.11(1)	.85
			D_{20}	.22	.001(1)	.006	.05(2)	.001(1)	.006
III	193	291.5	D_{50}	3.5	.01(1)	.56	.9	.01(1)	.24
			D_{90}	24	.11(1)	1.5	6.0	.11(1)	21.0
			D_{20}	.41	.001(1)	.34	.3	.001(1)	.006

Notes: All grain size values in millimeters

* River miles are from the mouth of the Sangamon River where it meets the Illinois River (Healy, 1979)

(1) Organic silt from the central portion of pools having a depth of 12" or more, one sample analyzed

(2) Estimated on the basis of laboratory analysis of surface material and visual inspection of materials in observation pits

observed at transect 1. As described before, the riffles at transects 7 and 13 have a deep thalweg cut along one bank. The silty sand deposited in the low-flow channel is more characteristic of pools at this site. Thus the results of the grain size analysis for the samples that do not include material from the thalweg are more representative of riffle bed material.

At Site III, there is little variation in materials across the riffles at transects 1 and 19, and samples taken at these locations are representative of these riffles. The bed material at the two middle riffles at Site HI, transects 7 and 13, is similar. At these riffles there is a distinct variation in grain size across the stream channel, from cobbles, coarse gravel, and sand to medium sand with very little gravel and no cobbles. However, unlike the conditions at Site II, there is no distinct thalweg or low-flow channel. At transect 13 (where multiple samples were taken), medium sand was observed to cover a large portion of the surface of the area identified as a riffle. The composite samples provide the best single representation of the bed material.

The range of median particle diameters shown in Table 7 illustrates the variability of the riffle material. However, the apparent degree of variation is ' somewhat exaggerated by the unit of measurement (1 mm = .039 inch). The D_{50} values determined for the riffle material samples at Site III and listed in Table 7 vary from 0.4 to 15 mm. The 14.6 mm difference is equal to 0.56 inch. These grain size values fall within the ASTM-ASCE classifications of medium sand to fine gravel (Table 6). At Site III, transects 13,14, and 15 he on the same long riffle. The range of D_{50} and D_{90} values obtained for the non-composite samples demonstrates the possible error if only a single sample is used to classify the bed material at a riffle.

The typical surface grain sizes for riffles at the three sites, listed in Table 10, are not significantly different. Using the ASTM-ASCE grain size classification given in Table 6, the D_{50} values fall within the range of coarse sand, the D_{90} values within the range of coarse gravel, and the D_{20} values within the range of fine sand.

Observation pits were dug at selected riffles to evaluate the representativeness of the Shelby tube samples of subsurface material. The coarsest materials were found on the surface of the riffles. This is illustrated by the schematic line diagrams documenting subsurface materials observed at the pits (Table 8). Visual observations and samples of the top 10 to 20 inches at the three sites indicate a streamwise progression from predominantly fines (silt and clay) at Site I, to a mixture of coarse-grained material in a matrix of silt and clay at Site II, to predominantly sand and gravel at Site III. At Site III, development of an observation pit was attempted at transect 13 to explore below the coarse material containing gravel and cobbles. Large gravel and cobbles were observed through the first 4 to 6 inches of the bed, but deeper exploration would have required a pit with a very large diameter to dislodge the larger stones. To deepen the pit would have noticeably disturbed the channel bed.

The organic silt found at Sites II and III covered much of the pool areas. The organic silt is likely a seasonal feature. The depth of the organic silt deposits greatly interfered with sample collection at the pools. Samples were taken at areas which may be classified as transition zones. These samples are expected to be indicative of the firm channel-bottom material at the pools, although pool bed material may be somewhat finer than found at the transition zone. Samples of the top 3 inches typically have larger median particle diameters than those determined from samples of the top 8 to 14 inches. This is similar to the vertical variation of material found at the riffles. The D_{20} values listed in Table 9 are in the range of fine sand at the surface and in the silt and clay range for the deeper samples.

Comparison of Laboratory Sieve Analysis and On-Site Measurements

The results of the site measurement of particle diameters following Wolman's procedure are shown in Table 7 along with the results determined from the laboratory sieve analysis. The values determined following Wolman's procedure demonstrate the surface distribution of grain sizes. These values are consistent with field observations. Comparable grain size values are higher than those obtained from the weight distribution determined from the sieve analysis. This is consistent with Wolman's findings. The greatest differences are at Site I and Site III. Several factors related to the field conditions and the methods of sampling employed in this study may contribute to these differences. Material from the top 3 inches or so is collected with a scoop sampler for sieve analysis. Thus finer-grained material below coarse gravel and cobble-sized stones is collected. This finer material covered by the coarse material is not considered in Wolman's sampling process and will shift the laboratory results to lower values. Infrequent large cobbles (6 to 8 inches) may not be collected for laboratory analysis, and on-site measurement of this type of material using Wolman's grid will tend to shift the grain size distribution to larger values.

The Wolman procedure has some advantages over the traditional method of grain size analysis, particularly for stream habitat assessment. Particles over the entire area of the riffle (or reach if desired) are examined, circumventing the possibility of collecting an unrepresentative sample. The surface area distribution of bed materials provides a description of exposed materials and roughness of the channel, which are factors influencing the quality of the stream habitat. Measurement of the grain sizes in the field took two field technicians approximately 1 to 2 hours per riffle. For this particular study the cost was slightly less than laboratory sample analysis. The procedure is limited in application to small streams and sites where the depth of water is such that material can be collected by hand.

Basinwide Variation of Bed Surface Materials

Observations of bed material particle size in various rivers have led to the general theory that median particle size (usually identified by D_{50}) decreases in the downstream direction. Simons and Senturk (1977) express this trend mathematically as $d_x = d_O \exp(-bx)$ where d_x= median size of bed materials at distance x downstream of a reference station, d_o = median size of bed material at the reference station, and b is a wear rating coefficient. Results of the grain size analysis of bed material from Sites I, II, and HI show only minor variations in the median particle diameter in the stream wise direction, with the exception of the absence of extensive silt deposits in the pools at Site I. Visual inspection of surface samples taken along Kickapoo Creek in the Salt Creek Basin indicates that riffle material becomes coarser in the downstream direction.

To better assess the streamwise variation in bed materials in the Sangamon River, data from other studies of bed material were considered. Median particle diameters determined by laboratory analysis for two reaches on the Sangamon River and one reach on Kickapoo Creek are reported by Herricks et al. (1983). Four samples from each reach were analyzed. The samples are not identified as to whether they are from riffles or pools. Visual observations of particle sizes along three reaches of the lower Sangamon are reported by Clark et al. (1987). On the basis of these recorded visual observations, a range of particle diameters was estimated. The locations of these reaches are given in Table 3.

The information from these studies is shown together with the data from this study in Figure 12. Grain size is plotted along the logarithmic ordinate scale, and distance from the basin divide is shown along the abscissa. The semi-logarithmic plot is consistent with the expression given previously for the streamwise variation in median particle diameter (D_{50}). The D_{50} values determined from the laboratory analysis of samples taken in this study are shown by solid circles for samples taken from riffles and by closed triangles for samples taken from pools. The typical values listed in Table 10 are plotted with open circles and open triangles for riffles and pools, respectively, at each study site. Data from the Herricks et al. study are shown with an

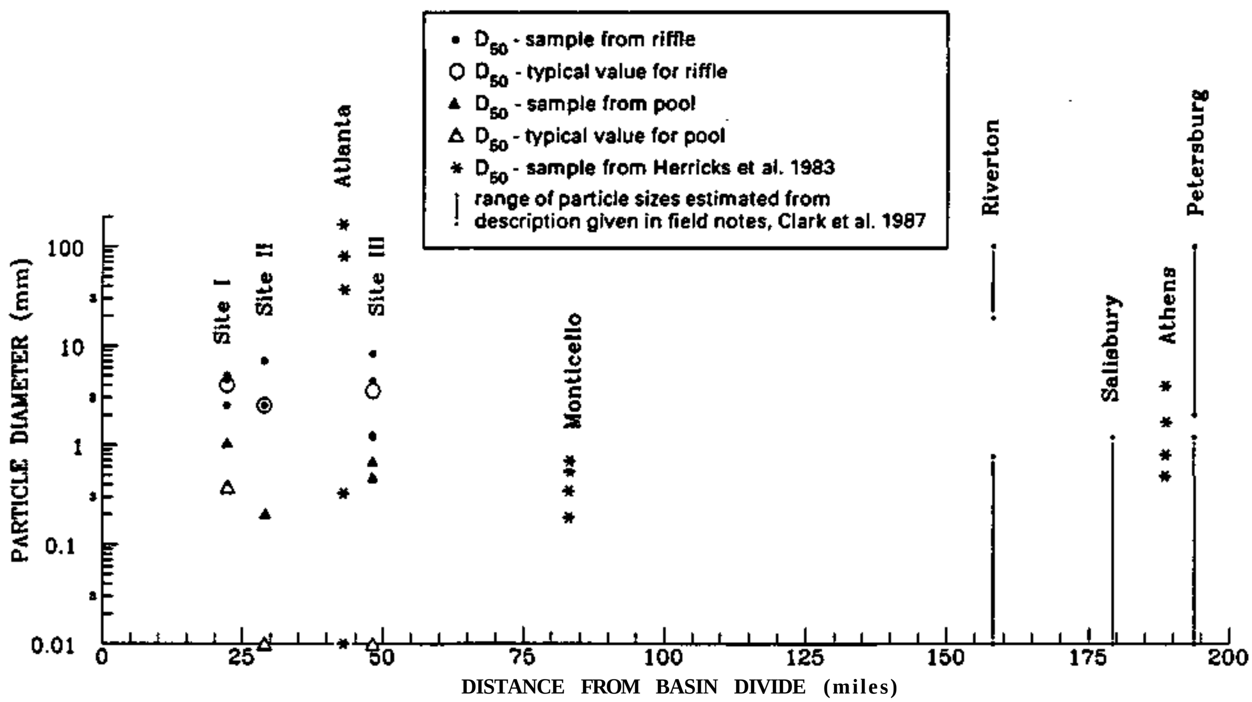


Figure 12. Basin wide variation of bed materials

asterisk. Ranges of grain sizes estimated from field notes (Clark et al., 1987) are shown with vertical bars.

The particle diameter values plotted in Figure 12 do not indicate a clear trend of decreasing magnitude with distance from the basin divide. The locations of the sites relative to the two physiographic regions of the basin provide some explanation for the lack of a consistent trend in the D_{50} values. The locations of each site from all three studies are shown on the basin map in Figure 2. The highest values reported are from the Atlanta reach. This may in part be attributable to its location in the vicinity of the Shelbyville Moraine, which is also shown on the map in Figure 2. Generally lower values are found at Sites I, II and III and at the Monticello reach located in the Bloomington Ridged Plain than at the remaining reaches located in the older Springfield Plain.

Differences in the conditions under which the samples were collected may create additional scatter in the data. Samples collected in the course of this study were obtained during extreme low-flow conditions, and velocities were frequently negligible. Thus it was possible to collect the samples with less problem of fines being washed out while the sample was retrieved from the streambed. During higher flow conditions, greater depths and higher velocities increase the potential of washing fines from the sampler as it is pulled from the water. A better retrieval of fines in the samples collected for this study would be reflected in lower D_{50} values than might be determined for samples collected under average streamflow conditions.

Density of **Bed Material and Correlation** with **Penetrometer** Data

In addition to the grain size analysis, the nature of bed material below the channel surface was investigated by determining the density of selected samples and exploring the consistency of material throughout the reach with a penetrometer.

Eleven samples were collected for density analysis: three at Site I, three at Site II, and five at Site III. Samples were collected with a 2-inch-diameter Shelby tube driven into the streambed. The length of sample collected was determined by measuring the distance from the top of the tube to the sample top both in place and after extraction. By following this procedure, field determinations could be made of the volume of the sample and of any loss of sample material when the tube was extracted. In most cases two Shelby tube samples were collected at each location: one for density analysis and one for grain size analysis. The sample density was determined by weighing the sample before and after laboratory oven drying. The dry density is computed as the mass of the dry material divided by the sample volume. The dry density in kilograms per cubic meter (kg/m^3) was converted to dry unit weight (pounds per cubic foot, or lbs/ft^3), as these units are still more commonly used in construction. The unit weight is directly proportional to the dry density, given the same gravitational constant.

For coarse-grained soils, the resistance of a soil to penetration is proportional to density. A penetrometer is a standard instrument used to measure the pressure required to force a 1/2-inch-diameter rod through soil. A precisely designed cone-shaped tip is screwed into the end of the rod. The higher the pressure dial reading, the greater the density of the material. The penetrometer provides a ready means of identifying similar deposits of soil without the expense of laboratory analyses of samples. The penetrometer was also used to determine the depth to the firm channel bottom. A Corp of Engineers penetrometer was used. A 4-foot extension rod was fabricated for the penetrometer, which has a standard length of 18 inches. The extension rod enabled the field crew to operate the penetrometer in several feet of water and, as was often the case in this study, to penetrate several feet of loose deposits to determine the depth of the firm channel bottom. Readings up to 300 pounds per square inch (psi) can be read from the pressure dial.

The penetrometer is hand-operated. Increments of 3 inches were marked on the rod so as to determine the depth for a given dial reading. The procedure followed was to have one field person force the rod into the channel bottom while the second field person recorded dial readings. The same field person operated the penetrometer for all readings to minimize differences in technique. Multiple probes were made at some locations to evaluate the consistency and repeatability of the readings. For the most part, readings from multiple probes at the same location were comparable. Absolute differences in pressure readings were typically within 30 psi, and trends were consistent.

The laboratory-measured dry unit weight and typical penetrometer readings near the sampling point for the 11 samples analyzed are given in Table 11. Multiple penetrometer probes were made in the vicinity of each sample collected for density analysis to determine representative values. In Table 11 the location of each sample is noted by the transect number and is identified as being from a riffle, pool, or transition zone. The length of the sample is noted. Samples represent approximately the top 12 inches of the streambed, varying in length from 8.4 to 14.9 inches. The length of the sample indicates the approximate depth of sampling. Selected grain sizes and the gradation of the companion samples taken at the same location are also given. The

Table 11. Unit Weight and Penetrometer Readings of Subsurface Bed Materials

	Trans No.	*Sample length (in)*	γ_d *lbs cuft*	*/ D_{20} (mm)*	*D_{50} (mm)*	*D_{90} (mm)*	*Gradation*	*Typical penetrometer readings, psi DEPTH 3"*	*6"*	*9"*	*12"*	*15"*	*18"*
Site I													
1	1(R)	11.6	103	.001	.014	1.5	well	100	100	200	200	200	
2	7(R)	9.9	107	.001	.016	.47	well	100	60	200			
3	4(P)	11.5	104	.007	.33	8	gap	100	120	200	200	200	
Site II													
4	7[3](R)	10.8	92	(.22	2.5	16)[2]	well	220	300	300			
5	19(R)	14.9	94	.17	.44	2.2	w.u.	100	200	300	300		
6	10(P)	10.5	64	.006	.2	.85	gap	10	10	80	80	160	
SitelH													
7	1[4](R)	8.5	69	(.39	1.2	10.7)2	well	220	300				
8	13[5](R)	8.4	83	.2	.5	1.5	uniform	40	60	240			
9	15(R)	12.6	85	.17	.3	.9	uniform	40	40	50	140		
10	6(T)	12.9	88	.38	.6	1.8	uniform	40	40	40	120	140	
11	9(P)	10.9	23	.006	.24	21	gap	100	0	0	0	0	220

Notes:

All grain size values in millimeters

(R) riffle

(P) pool

(T) transition

w.u. weathered uniform

γd dry unit weight, lbs/ft^3

1 results of grain size analysis of companion sample taken at same location

2 results of grain size analysis of top 3"

3 coarse sand and gravel at top 3", sand and gravel mixed with silt and clay identified through remaining sample depth in observation pit at this transect

4 coarse sand and fine gravel identified through sample depth in observation pit at this transect, appeared the same as surface material

5 medium to coarse sand identified through sample depth in observation pit at this transect; from grain size analysis of top 3", D_{50} = .5 mm, D_{90} = 1.5 mm, D_{20} = .2 mm; surface material at this riffle varied, material at the opposite bank consisted of medium sand, coarse gravel, and cobbles.

samples are numbered 1 to 11 in Table 11 to simplify identification for the purposes of discussion.

The sub-surface samples taken from Site I are for the most part composed of fines, silt, and clay, with some fine to medium sand and fine gravel. The sub-surface samples taken from Sites II and III are for the most part composed of fine to medium sand. The D_{20} values of samples 6 and 11, taken at pools, show the presence of some fines. On the basis of a visual inspection these samples appeared to have some organic silt present similar to that found on the surface of the pools at Sites II and III.

There is a very good agreement between the dry unit weight, grain sizes, and penetrometer readings. The densities determined are fairly consistent within a reach. The density of samples taken at riffles decreases from Site I to Site III in the downstream direction. At Site I, sample 3 (taken in a pool) has essentially the same density as riffle samples. A large fraction of silt and clay was observed below the surface at Site I, which is demonstrated by the smaller grain sizes, particularly D_{20}. At Sites II and III samples taken in the pools (numbers 6 and 11) have considerably lower density than samples taken at riffles. Although densities of the samples taken at the riffles are greater at Site I than at Site II, the penetrometer readings are somewhat lower at Site I than recorded at Site II. This is likely due to the high proportion of fines, which allow easier penetration. Comparing the density of samples 5, 8, 9, and 10, which are uniformly graded and have similar grain size distributions, higher penetrometer readings were measured in the denser soil. Samples 4 and 5 from riffles at Site II have about the same density; the slightly higher penetrometer readings in the vicinity where sample 4 was taken may be attributable to the 3-inch layer of coarse sand and gravel at the surface, which was not present at transect 19 where sample 5 was taken.

At the Site III riffle where samples 8 and 9 were taken, bed material varies across the channel from cobbles, coarse gravel, and medium sand to medium sand with no gravel or cobbles. Samples 8 and 9 were retrieved from the sandy portion of the riffle in the vicinity of the observation pit (see Table 8). High penetrometer readings at the surface, e.g., 240 to 300, were frequently obtained when very coarse material was present at the surface (samples 4 and 7, for example). Similar penetrometer readings were obtained in the vicinity where samples 4 and 7 were taken; however, there is considerable difference in the laboratory-determined density. Some explanation of the low density of sample 7 as compared to sample 4 may be found by referring to the visual classification of materials found in the observation pits, shown in Table 8. In the vicinity of sample 4 (from Site II, transect 7), the coarse material extends only about 3 inches below the surface, after which there is evidence of silt and clay. Coarse sand and fine gravel were observed through the entire depth corresponding to the depth of sample 7 (from Site HI, transect 1). The lower density of sample 7 may be influenced by a higher proportion of gravel than observed in other samples, and by the absence of fines.

In summary, the analysis of the sample densities in relation to penetrometer readings and visual observations shows that for soils with similar grain size distributions, the penetrometer readings increase with increasing density. Consistently high penetrometer readings appear to correspond to a noticeable fraction of gravel, but these penetrometer readings do not provide information on density. At riffles, fines (silt and clay) were observed a few inches below the surface at Site I. A mixture of coarse material (sand and gravel) in a matrix of silt and clay was observed about 3 inches below the surface at Site II, and no silt or clay was observed at Site III. The increase in the density of riffle samples from Site I to Site III may be related to the presence of fines which, compared to coarse-grained material, can pack more closely together and/or fill voids between coarse-grained soils. Within a reach, the consistency of the penetrometer readings demonstrates that they provide a good relative basis for comparing bed materials below the surface.

Penetrometer Exploration of Bed Materials

Penetrometer readings were taken at six equally spaced points across each transect in each reach. This program of penetrometer exploration was conducted to assess if a consistent pattern of channel bottom deposits exists throughout the reaches. Penetrometer readings versus depth are plotted with channel cross-section elevations in Figures 13,14, and 15. These plots show the position of the penetrometer reading in relation to the elevation of the channel bottom, channel sides, and thalweg. In nearly all cases, penetrometer readings increase with depth.

At locations (typically riffles) where fine to coarse gravel was present, it was difficult to force the penetrometer through the deposit. Penetration of at most a few inches was possible, with readings from 250 to 300 (300 is the maximum reading). This situation was typical of riffles at Sites II and III, as was noted above in the discussion of bed material density. In the central portion of pools, particularly where a thick layer of organic silt was present, a reading of zero frequently was assigned as the penetrometer would advance through the material with little or no pressure. At locations other than the coarse-grained riffles, penetrometer readings through the first 18 inches below the surface ranged from 0 to 300; the majority were under 200. The

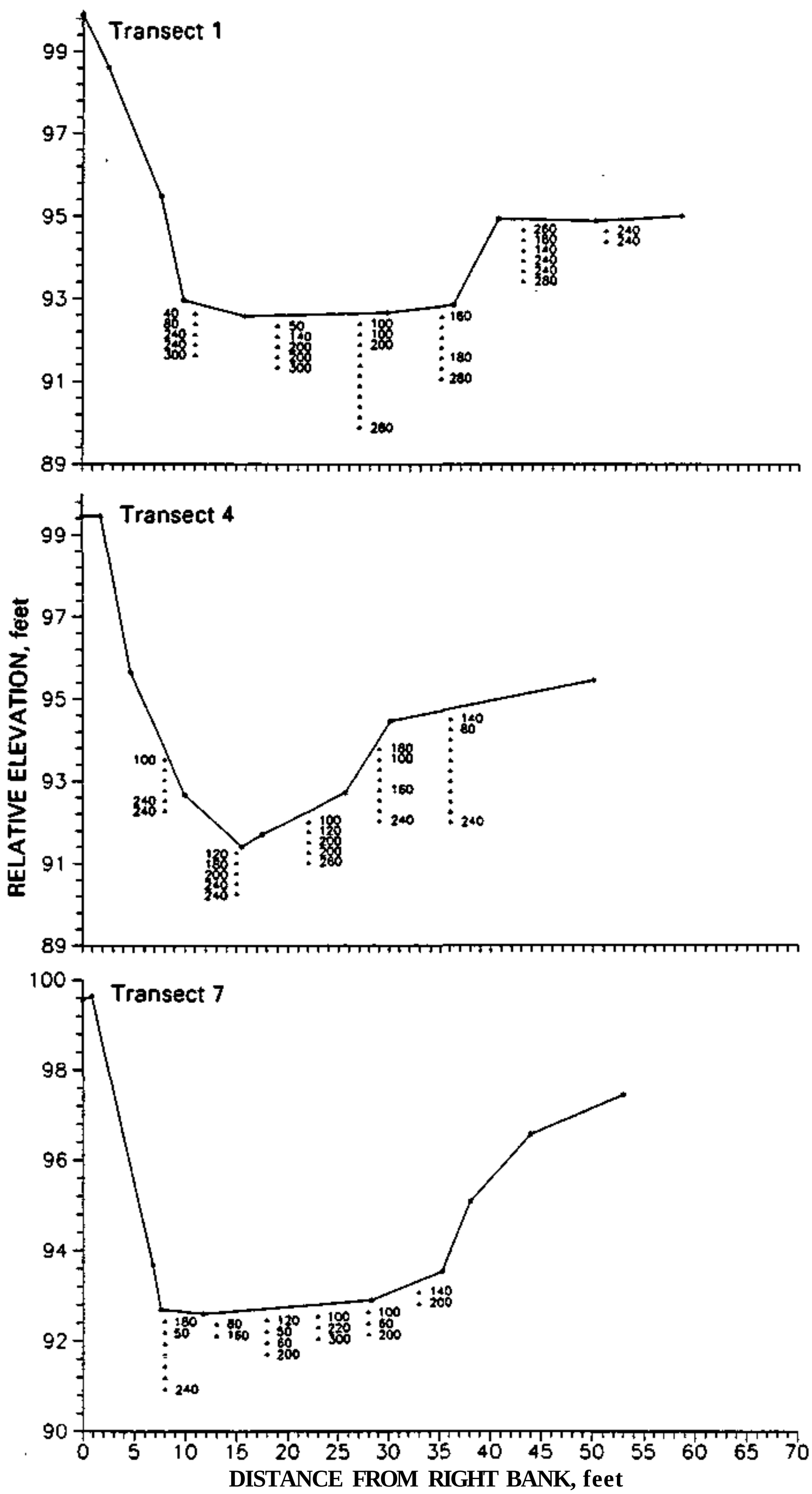


Figure 13. Three stream cross sections and penetrometer readings at Site I

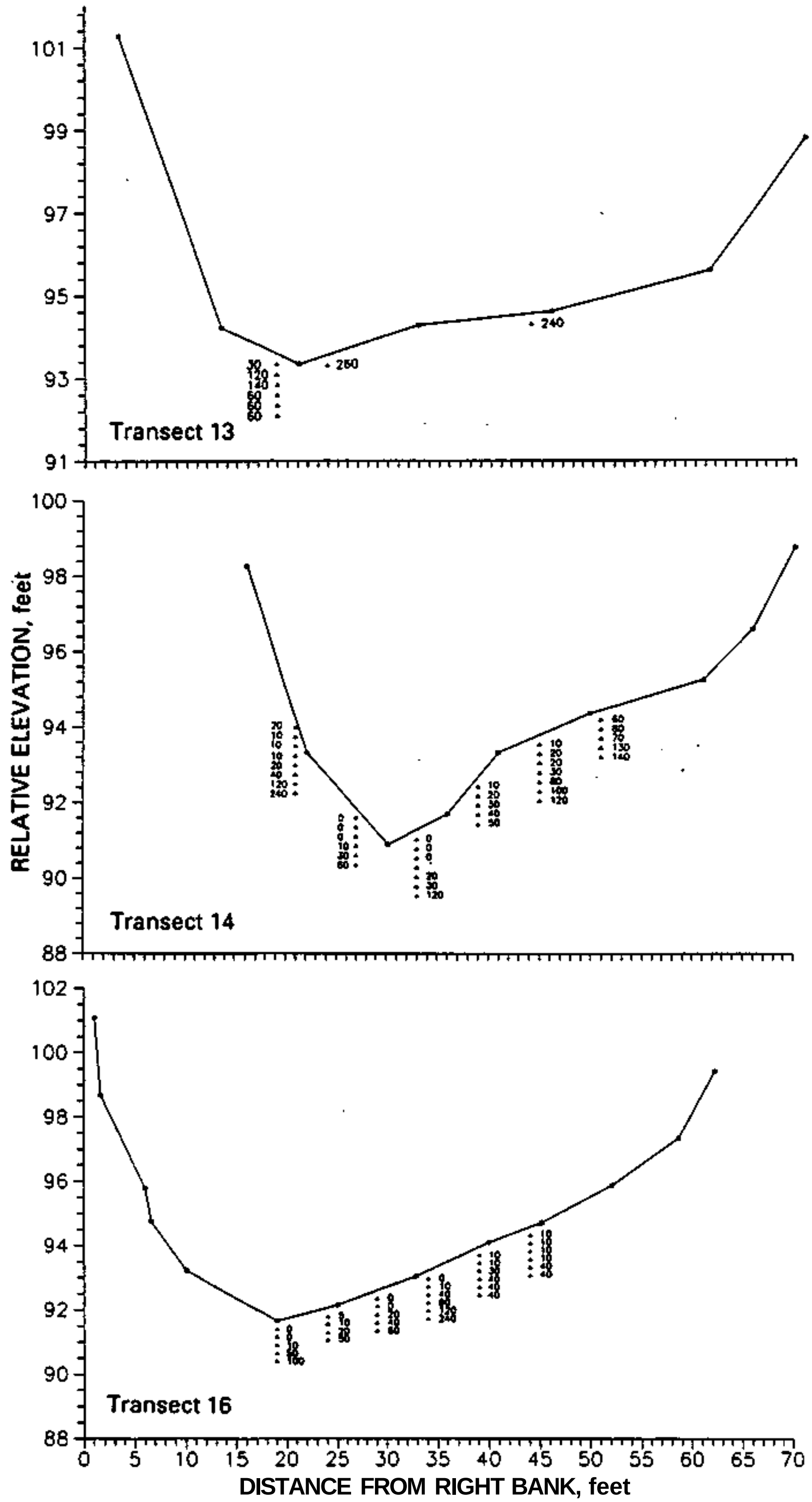


Figure 14. Three stream cross sections and penetrometer readings at Site II

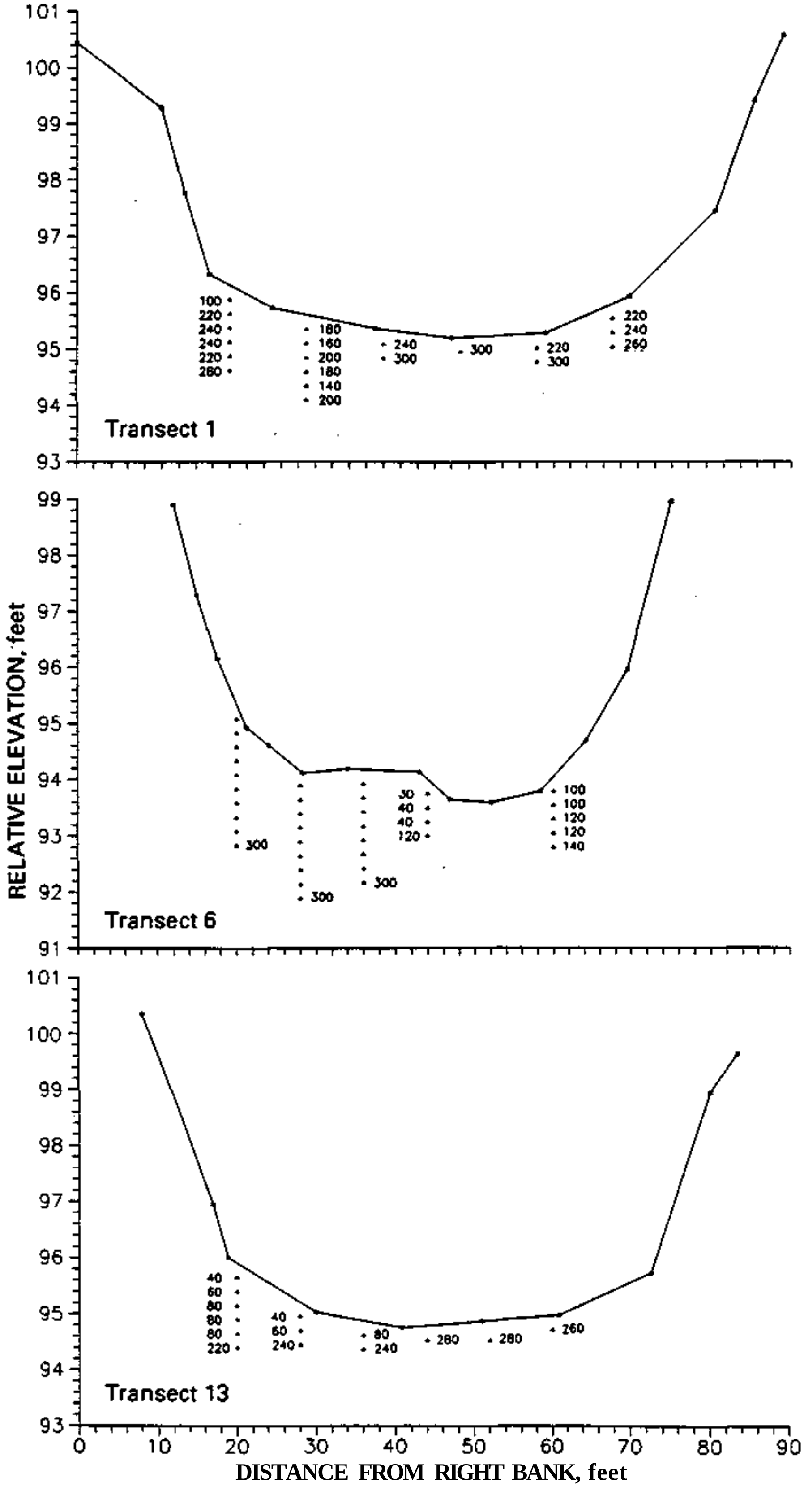


Figure 15. Three stream cross sections and penetrometer readings at Site III

patterns of penetrometer readings at Sites II and III were comparable. At Site I the penetrometer readings show a consistent pattern from riffle to pool throughout the reach. However, the penetrometer readings at Site I do not indicate the very loose pool deposits observed at the other sites. Site I does not have the organic silt deposits in pools as seen at the other sites.

There was little difference between penetrometer readings from riffles and pools at Site I. The values shown in Table 11 are typical of those observed. Most readings ranged between 100 and 240 psi over the first 12 to 18 inches below the surface. An exception to this was found at riffle thalwegs, where readings from 50 to 80 psi through the first 3 to 6 inches were observed, and values of close to 200 psi were not observed until depths of 12 inches or more were reached. Penetrometer readings were typically taken through a depth of 18 inches, and at a few cross sections a depth of 30 inches was reached. On the basis of the penetrometer readings and sample density, it appears that the first 18 inches or so of the channel bed below the surface at this site is essentially the same throughout the riffle and pool sequences.

Riffle bed material at Site II varied from riffle to riffle and, at some riffles, across the channel; penetrometer readings were likewise variable. Where coarse-grained materials were visible at the surface (transects 7 and 13), the typical pattern was for penetrometer readings in the range of 240 to 300 psi and penetration of only a few inches. Lower readings in the range of 100 to 200 psi over the first 3 to 6 inches were noted at sandy areas of the riffles where little or no gravel was present. In the streamwise direction, progressively lower penetrometer readings were obtained going from riffles to pools, and conversely, progressively higher readings were found going from pools to riffles. At transects adjacent to those located at the center of riffles, penetrometer readings generally varied from 20 to 240 over the first 12 inches below the surface. In the central portion of the pools, readings varied from 10 to 50 psi over the first 12 to 15 inches below the surface, and values in the range of 100 to 120 psi were typical at 18 to 24 inches.

The general pattern of penetrometer readings at Site III is comparable to those found at Site II, although the magnitude of the pressure dial readings at transition zones and pools were typically lower at Site III than at Site II. Similar to Site II, at sections of the riffles where there is an abundance of gravel or coarser material, penetrometer readings were 240 to 300 psi, and at most the penetrometer could be forced through the top 3 to 6 inches. Along sandy portions of the riffles and in the thalwegs where little gravel was observed, readings on the order of 200 psi were not reached until a depth of 9 inches or more. Transects adjacent to riffles generally showed readings from 20 to 80 over the first 12 inches, reaching 140 to 180 at depths of 15 to 18 inches. In the central portions of pools, the material was so loose that few readings could be obtained, as the instrument would advance under its own weight. With the 4-foot extension rod, the firm bottom was probed and found from 2 to 5 feet below the surface. The readings associated with sample 11 in Table 11 are typical of the pools, and those for sample 10 in Table 11 are illustrative of transition zones (transects adjacent to those defining riffles).

In summary, the purpose of the penetrometer survey of the stream reaches was to investigate the similarity or variability of the soil structure of the channel bed throughout each study reach. The resistance of the soil to penetration is proportional to soil density, and the penetrometer readings provide a numerical index for comparing the density of the material forming the channel bed. As the penetrometer readings generally show a good correlation with the laboratory-determined sample densities, the density of the channel bed material along each reach may be inferred from the penetrometer readings. Correlation of the penetrometer readings, laboratory analyses of density and grain size, and visual inspection of material provides insight as to the type of deposits forming the channel bed along each reach. The penetrometer data demonstrate that immediately below the surface (top 12 to 18 inches), the bed material at Site I is fairly uniform throughout the riffle and pool sequences. The coarse-grained soils at the surface are underlain by silt and clay. The penetrometer probing at Sites II and III revealed the depth of very loose surface deposits in pools: 2 to 3 feet deep at Site II, and 2 to 5 feet deep at Site III. A greater variability in bed materials was found at Sites II and III than at Site I. The penetrometer data show that the same pattern of dense deposits at riffles and loose deposits at pools are repeated throughout the riffle and pool sequences of Sites II and III, which are characterized primarily by coarse-grained soils.

BASINWIDE FLOW MODEL

Background Information

Flow depth, velocity, and substrate have been identified as the most significant hydrogeologic channel characteristics defining the suitability of the aquatic environment for various fish species (Stalnaker, 1979). These parameters are directly related to streamflow regimen and, as they vary from riffle to pool, they create the continuum of flow conditions necessary to support various aquatic organisms and fish species at different life stages. Other significant factors are temperature and vegetation.

The Instream Flow Incremental Methodology (IFIM), developed by the Cooperative Instream Flow Service Group (IFG) of the U.S. Fish and Wildlife Service, is the state-of-the-art methodology for defining the relationship between flow parameters (depth, velocity, and substrate) and usable habitat. The availability of useful habitat in a stream is quantified through the calculation of an index variable, weighted usable area (WUA). The WUA of a stream can be calculated for various fish species and their life stages under any given flow conditions. In the IFIM the availability of different types of habitat is determined by conceptually segmenting the stream into cells. Each cell represents a different environment characterized by local values of depth, velocity, and substrate. The utility of the environment in each cell is independently evaluated by using fish preference indices for depth S(d), velocity S(v), and substrate S(b) (Bovee and Milhous, 1978; Bovee, 1982). The IFG has developed preference data (called preference curves) for more than 500 fish species and is continuing research to improve and expand its database (Loar and Sale, 1981; Milhous et al., 1984). The WUA of a stream reach is typically calculated by summing the product of the cell suitability index and the lateral flow surface area of the cell, a_i. The calculation is expressed mathematically:

$$WUA = \sum_{i=1}^{N} S(d_i) \times S(v_i) \times S(b_i) \times a_i \qquad (5)$$

where N = number of cells. The geometric mean of the suitability index values or the minimum index value are alternative formulations for the calculation.

Local values of depth and velocity, such as found in riffles and in pools, must be known to evaluate the WUA for a given discharge. Flow modeling of local depths and velocities is a critical aspect of the IFIM, because without the simulated hydraulic data, WUA could be determined only for field-measured flows.

A methodology for basinwide flow modeling and habitat assessment using IFIM has been developed and successfully applied to the Sangamon River Basin and the Vermilion River Basin in Illinois (Singh and Broeren, 1985; Singh et al., 1986, 1987). Basin hydraulic geometry relations are used to define average W, D, and V for a stream reach with specified drainage area and length. The range and frequency of local values of depth and velocity are determined from probabilistic distribution models developed from field data. The parameters of the distribution functions, such as the standard deviation of depth, S_d, vary from basin to basin and along the stream network. The basin flow model simulates a number of paired values of local depths and velocities, with each pair representing a percentage (say, 1 percent) of the specified reach. The preference indices for a target fish species for each simulated value of depth and velocity are determined, and the WUA is calculated from equation 5. The purpose of the basin flow model is to supply needed hydraulic data for habitat assessment on a basinwide scale without the prohibitive cost of individual site surveys to collect hydraulic data for each stream. The information can be used with a biological assessment of stream conditions by water resource planners.

The probabilistic distribution models were developed in a previous study (Singh et al., 1986) from field data collected in five reaches in the Sangamon Basin (up to Riverton) and four reaches in the South Fork Sangamon Basin. Depth and velocity data were collected at two different discharges in each reach. The depth and velocity measurements made as part of this study validate the basic premise of the flow model for discharges in the low-flow range. The information on bed materials was examined in terms of its relationship with the depth and velocity distributions. This provides a third parameter defining the aquatic habitat for evaluation of its suitability to support various aquatic life forms. The depth and velocity models for predicting local variations throughout a reach are discussed in detail by Singh et al. (1986). An in-depth explanation of the flow model relations will not be attempted here. Expressions and relationships used in the flow model will be summarized as needed to explain the relevance of new findings or data.

Depth and Velocity Measurements

Depth and velocity were measured at six equally spaced locations across each of the 19 transects in each reach, making 114 pairs of depth and velocity readings. These measurements were conducted for three different discharges in each reach. The discharges measured correspond to annual flow durations between 57 and 89 percent, thus representing low to very low flow conditions. The dates of measurement, the discharges, and their annual flow durations, as well as the reach average width, depth, and velocity are given in Table 12.

During very low discharges (flow duration approximately 80 percent and greater), many cross-sectional depths were too shallow and/or velocities were so low as to be unmeasurable with standard instrumentation. Velocity, and thus discharge, could be measured only at cross sections where the low-flow channel narrowed such that the flow converged. As a measurable discharge was observed at some cross sections, it was necessary to estimate a velocity for those sections where no velocity readings could be made.

Comparison of Field Data and Hydraulic Geometry Equation Results

As observed by Singh et al. (1986), the reach average values of field-measured width, depth, and velocity differ from those predicted by hydraulic geometry equations. This difference is attributed to differences in the field data and the data used to develop the equations. The hydraulic geometry equations are developed from data collected specifically for discharge measurements and appear to best represent flow characteristics typical of near-riffle areas, but the arithmetic average of the field data includes information from both riffle areas and pool areas. Thus, the field data values presented in Table 12 are *reach average values,* while the hydraulic geometry equations are expressly meant to define flow parameters at the measurement cross section.

For the purpose of predicting local variations in depth and velocity throughout the reach, which is needed for habitat assessment, the reach average values are useful. Thus adjustment factors are needed to modify values predicted by the equations to better reflect reach average values. Data from the present study and sites 1 through 9 listed in Table 3 (from a previous study of the Sangamon and South Fork Sangamon Basins) show a consistent pattern in the relationship between the equation results and reach average values of W, D, and V. This is illustrated in plots of the ratio between the field data averages (W_f, Df, and Vf) and the values calculated from the hydraulic geometry equations (W_{hg}, D_{hg}, and V_{hg} using the appropriate flow duration and drainage area) versus annual flow duration, F, shown in Figure 16. The ratio of the reach average values to those from hydraulic geometry equations is fairly consistent for high to medium flows with flow durations from 10 to about 60 percent. At low flows (annual flow duration greater than about 60 percent), there is a consistent increase in the variation between the reach average values and predicted values. This implies that the flow characteristics in riffles and pools become increasingly variable as discharge decreases.

Table 12. Discharge and Average Values of W, D, and V
Measured in Study Reaches

Study reach	*Measurement*	*Start date*	*Q (cfs)*	*Flow duration (percent)*	*Arithmetic average values W (ft)*	*D (ft)*	*V (fps)*
Sangamon Main Stem							
I	a	7-11-89	3.00	68	12.71	0.65	0.27
	b	7-28-89	7.37	57	12.81	0.75	0.59
	c	8-16-89	2.31	71	12.04	0.65	0.22
II	a	7-18-89	2.09	82	19.00	1.25	0.07
	b	8-2-89	4.68	73	18.33	1.29	0.09
	c	8-17-89	1.85	84	18.78	1.26	0.05
III	a	7-31-89	12.03	75	28.72	1.41	0.15
	b	8-10-89	4.34	89	27.51	1.25	0.06
	c	9-29-89	36.13	61	31.21	1.80	0.36

Note: Q = discharge; W = width; D = depth; V = velocity

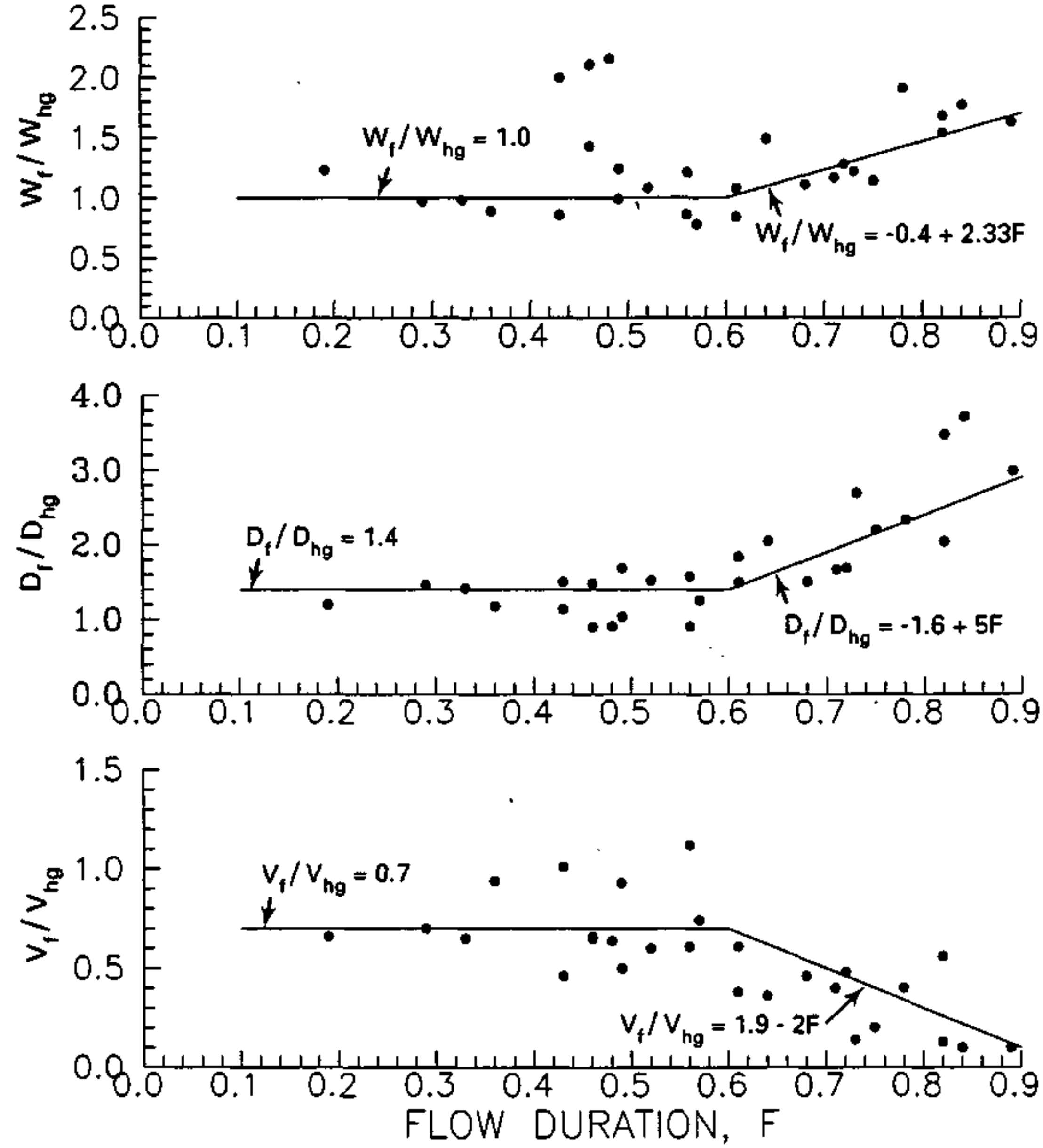


Figure 16. Hydraulic geometry adjustment factors for W, D, and V versus flow duration, F

Expressions defining the relationship between the results of hydraulic geometry equations and field data are shown with solid lines in Figure 16. Values of W, D, and V may be adjusted to better reflect reach average values by using multiplication factors computed from these equations. The adjustment factors vary with flow duration. These adjustment factors differ slightly from those given by Singh et al. (1986), as the hydraulic geometry equations have been revised. Also, the data collected during this study provided needed information for the low-flow range (high flow duration) to better predict the adjustment factors in that range of flows.

Standard Deviation of Depths

The standard deviations, S_d, of the 114 measured depths for each of the nine discharges measured (three discharges in each reach) were calculated. These standard deviations are plotted versus drainage area in Figure 17. Also plotted are the standard deviations of depths determined from similar field measurements at study reaches 1 through 9 as listed in Table 3. The standard deviation of depth is an indicator of the difference between riffle and pool depths. It increases with drainage area as the difference between riffle and pool elevations increases. The data collected as part of this study corroborate this observed trend for the low-flow range of discharges measured. A straight line shown on the plot is used to approximate the trend of increasing S_d with increasing drainage area.

The flow duration of the discharge at the time of the depth measurements is noted for each point in the plot. At most sites there is less than 0.1 foot difference in the S_d calculated from depths measured at different flow durations, although S_d tends to be higher for the lesser flow durations. The maximum difference between the straight line approximation and the plotted points is about 0.3 feet. This is also the approximate range of values seen when comparing values determined at different study sites with similar drainage areas.

The standard deviation of depth, S_d, is plotted versus the difference between average pool depth and average riffle depth, AD, in Figure 18. The average riffle depth was computed as the average of the depths measured at transects crossing riffles, and the average pool depth was computed as the average of the depths measured at the remaining transects. The graph illustrates the increase in S_d with increasing AD. The relationship between average difference in flow depths, the standard deviation of local depths, and the relative difference in channel bottom elevations at pools and riffles is demonstrated by comparing the computed AD and S_d to the difference between pool and riffle depths determined from the cross-sectional survey of each reach, allowing for

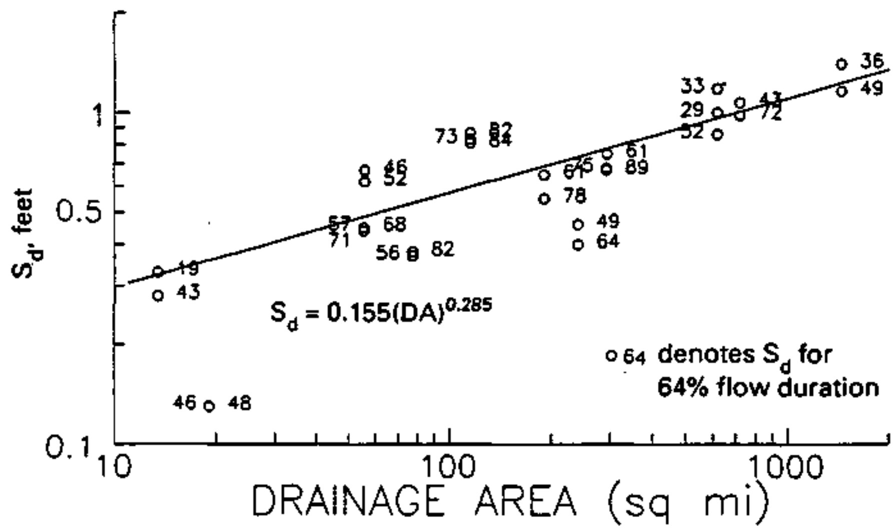


Figure 17. Standard deviation of depth (S_d) versus drainage area

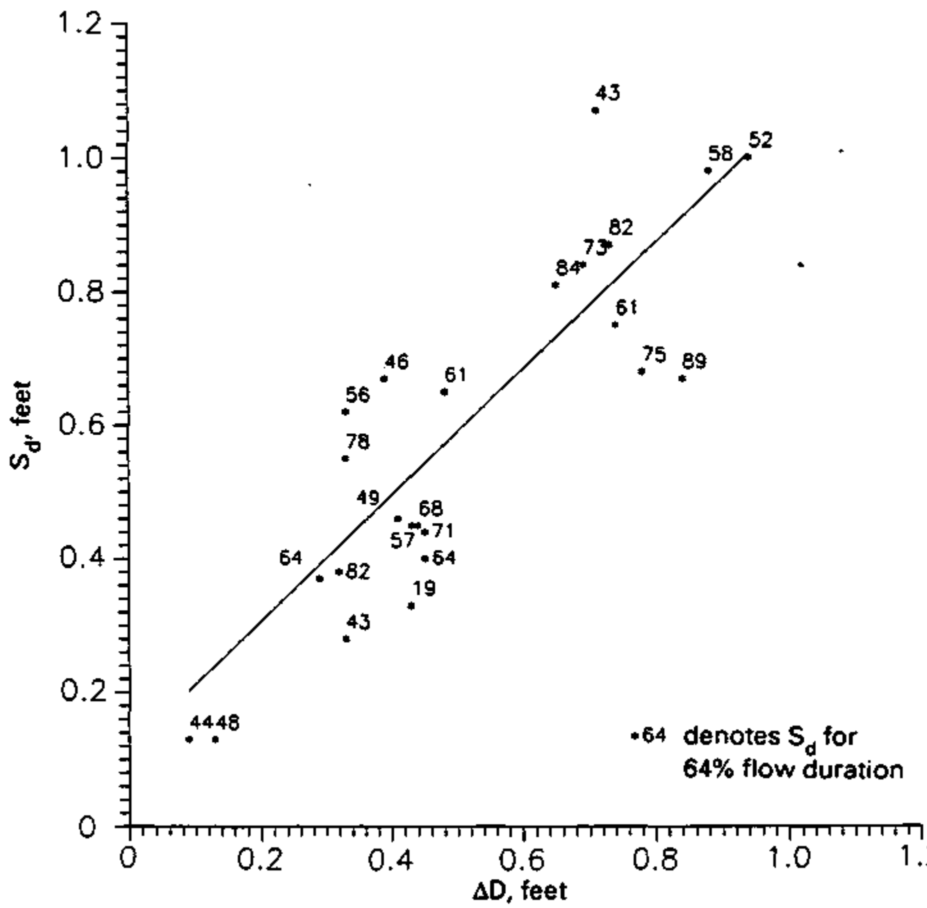


Figure 18. Standard deviation of depth (S_d) versus difference in average pool and riffle depths (AD)

the average slope of the channel bottom. On the basis of the survey data, the average differences between pool and riffle elevations are 0.4, 1.1, and 1.0 feet for Sites I, II, and III, respectively. The average AD and average S_d measured at Site I are 0.52 and 0.45 feet, respectively; at Site II they are 0.97 and 0.84 feet, respectively; and at Site III they are 0.87 and 0.7 feet, respectively. The longitudinal profile for Site III (see Figure 7) shows that the second pool is not well-defined. Thus the values for Site III may be slightly low. Given the terrain, the precision of the survey data is estimated as 0.1 foot. The precision of the flow depth measurements is about 0.05 foot. Considering that all 19 transects were not surveyed in each reach and given the precision of the measurements, AD determined from flow measurements is in very close agreement with the actual difference in the average channel bottom elevation between pools and riffles.

The curve drawn in Figure 18 approximates the relationship between AD and S_d. This relationship provides the link between the physical channel characteristics and the flow model parameter, S_d, used to estimate the range and distribution of local depths. Thus the effect on local depth of creating riffle-pool sequences having specified differences in relative depth can be estimated, as can the subsequent change in WUA.

Standard Deviation of Velocities

The standard deviations of the 114 measured velocities for each of the nine discharges measured were also calculated. The magnitude of the standard deviation of velocity (S_v) increases with increasing reach average velocity (V), and the relationship between S_v and V is approximately linear. The coefficient of variation, $CV_V = S_v/V$, also shows a consistent pattern. However, CV_V increases with decreasing velocities. The data from the current study field measurements confirm the rapid increase in CV_V as the reach average velocity decreases below 0.2 feet per second (fps). Thus when the reach average velocity is very low, there is greater variation in local velocities relative to the average velocity than is the case for higher velocity discharges. However, the magnitude of the range of actual velocities observed is greater for high average velocities. For reach average velocities between 0.3 and 0.8 fps, the corresponding standard deviation of velocity ranges from about 0.2 to 0.45 fps, with CV_V of 0.67 and 0.56, respectively. For reach average velocities between about 0.06 and 0.25 fps, S_v values range from about .12 to .3 fps, with CV_V around 2 to 1.2.

Distribution of Depth, Velocity, and Substrate

The joint distributions of local depths and velocities and observed substrate were investigated by using the field data collected at three different discharges in each reach. The grid pattern of sampling at the 19 transects provides 114 simultaneous depth/velocity pairs. On the basis of substrates observed in each reach and the particle diameters determined from the laboratory analysis of bed material samples, a substrate code was assigned to each pair. For simplicity the original substrate code proposed by the Cooperative Instream Flow Group (Bovee, 1982) was used. This code uses a single digit to describe each of eight different classes of bed material, from 1 for plant detritus to 8 for bedrock. Silt, sand, gravel, and cobbles have codes 3, 4, 5, and 6, respectively. The first decimal place is used to indicate a mixture between two classes. As the bed materials observed along the Sangamon are generally a mixture of silt, silt and sand, sand and gravel, or gravel and cobbles, the code is adequate to classify the materials.

Data analysis procedures used to develop the probability models for local depths and velocities in the basin wide flow model were repeated with the new field data. The field data collected for this study provide more complete information for discharges in the very low flow range. Following the previously established procedure provides a common basis for comparison. Depths were ranked from lowest to highest, and the cumulative nonexceedence probability was computed by using the formula $i/N+1$, where $i = 1:N$, and $N = 114$. Ten divisions of cumulative probability of depth between 0 and 1.0 were delineated, each corresponding to a probability interval of 0.1. Each depth, velocity, and substrate point (d,v,s) was coded as a riffle or pool measurement. The velocity and substrates associated with each of the ten divisions of depth probability were then considered. Generally the same patterns of depth and velocity associations and rankings were confirmed by the field data from this study.

More than 90 percent of the depth measurements made at riffles have associated cumulative probabilities of occurrence between 0 and 0.6, which are the lower depths. Riffles span approximately 30 percent of each reach; consistent with this observation, about half of the depths within this cumulative probability (0 to 0.6) range were taken at riffles. Data from riffles are fairly evenly distributed within the depth cumulative probability range 0 to 0.6. It follows that the substrate codes for bed material found at riffles follow the same pattern. The velocities in each depth probability interval were inspected. Overall, the highest velocity values within each group (defined by the probability interval) are also found at riffles. Thus about one-half the depths in the probability range (0 to 0.6) having the highest simultaneously measured velocities are also associated with riffle bed material conditions. Substrate codes for transition zones and pools were assigned on the basis of similar observations of depth, velocity, and substrate.

The distributions of local depths, velocities, and substrates are readily explained when channel form is considered. The greatest depths occur in the pools, and thus it follows that pool conditions are associated with the larger depth cumulative probabilities. Simultaneously measured velocities tend to be less than the reach average. The lesser depths (having cumulative probabilities 0.6 and under) and higher velocities are found at riffles. Those pairs of lesser depths (falling within the cumulative probability range 0 to 0.6) and associated lower velocities found at pool cross sections are typical of conditions near the bank. There is greater flow resistance at the bank, and thus lower velocity. Inspection of the pool cross sections in Figures 8, 9, and 10 shows the bed curvature near the banks, which demonstrates the occurrence of shallower flow.

Model Demonstration

The Sangamon basinwide flow and aquatic habitat model can be used to estimate weighted usable area (WUA) for streams throughout the basin up to the confluence of the Sangamon River and South Fork Sangamon River for discharges having annual flow durations between 10 and 90 percent. For the purpose of demonstrating the model output, WUA was calculated for a 100-square-mile drainage area stream for bluegill adult and juvenile life stages. The variation of WUA with flow duration is illustrated by the plot in Figure 19b. Flow duration is shown along the abscissa, and WUA per 1,000 feet of stream length is given as the ordinate. Figure 19a is a plot of the bluegill juvenile and adult preference curves for depth and velocity. The WUA is calculated as a product of the fish preference index for each combination of depth, velocity, and substrate. The low WUA for juveniles for flow durations of 10 through 60 percent is due to the relatively high velocities occurring at these discharges, which are unsuitable for the juveniles. The decrease in WUA with increasing flow duration for the adults is due to the shallower depths occurring during low flows.

To demonstrate the impact of channelization on availability of suitable fish habitat, a sample channel design was determined for a stream with a 100-square-mile drainage area, following standard procedures. Then WUAs for bluegill juvenile and adult lifestages were determined for the depth and velocity of flow expected over the range of discharges corresponding to annual flow durations of 10 to 90 percent. The constraints set on the channel design were that the slope would remain unchanged, the

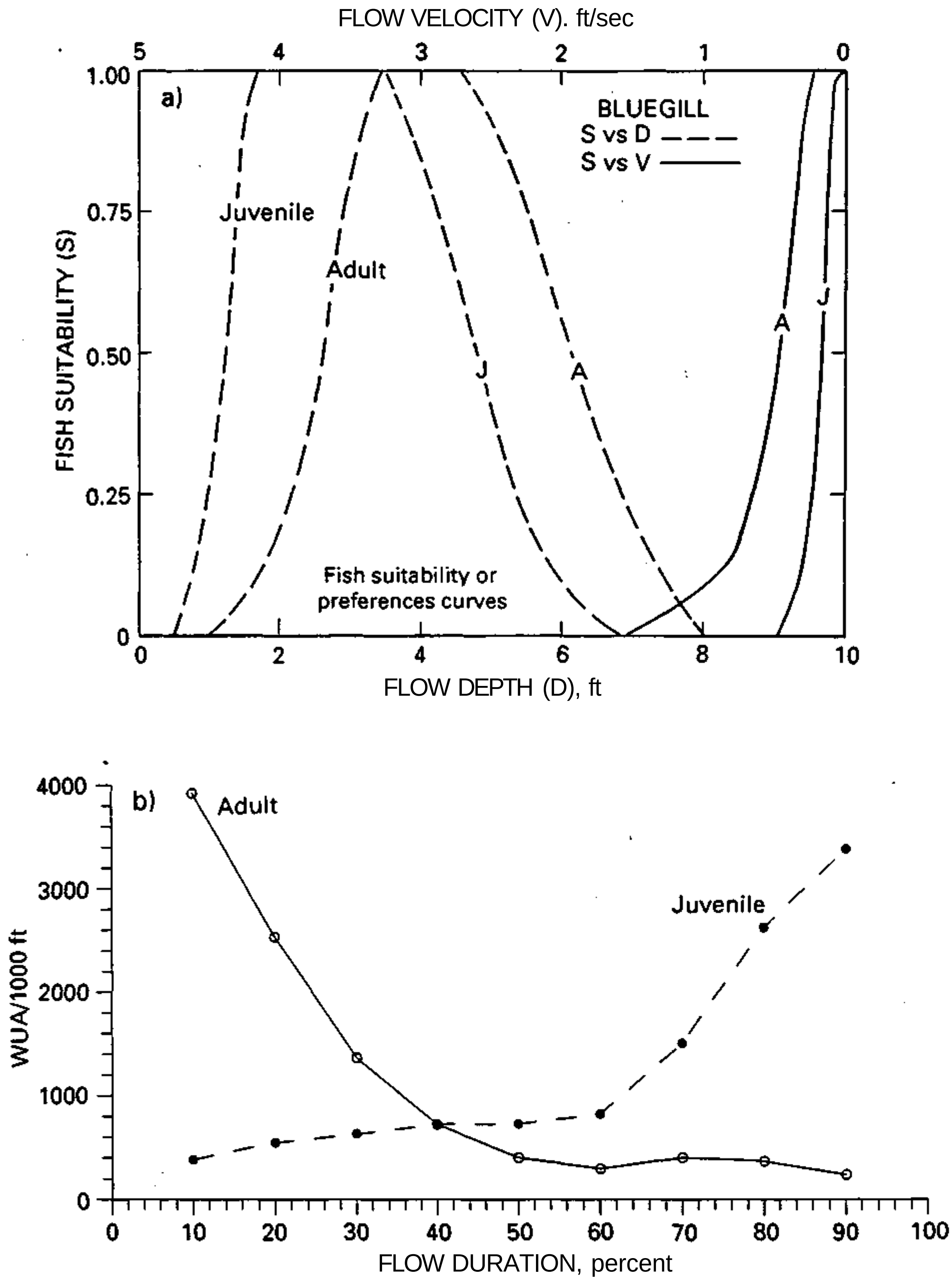


Figure 19. (a) Bluegill juvenile and adult preference curves for depth and velocity, and (b) variation of weighted usable area (WUA) with flow duration

channel shape would be trapezoidal, and the channel would have the capacity to pass a 5-year return interval flood. A 100-square-mile drainage area will be just upstream of Site II, and thus the average slope was taken as 0.025 percent (see Figure 4). Standard design practice is to calculate the 5-year return interval discharge by using the methodology and equations published by the USGS (Curtis, 1987). A side slope ratio of 1 to 2 is commonly specified and was used in the calculations as it is close to the existing bank slope. On the basis of the survey data for the existing channel at Site II, the bankfull depth is about 5.7 feet. This depth is a constraint given an unchanged channel slope. The necessary channel width was determined from an iterative solution of Manning's equation. The calculated 5-year return interval flood is 1,439 cfs, and given the above noted constraints, the minimum bottom width for a straight, clean trapezoidal channel is 53 feet. Given that the channel is uniform, Manning's equation is appropriate for calculating average depth and width of normal flow. The bluegill adult and juvenile suitability preferences corresponding to the calculated average depth and velocity indicate that the stream would be unsuitable for supporting either lifestage over this range of flows. The depth of flow calculated for flow durations from around 90 percent to 40 percent corresponds to preference indices of zero, and velocities calculated for flow durations around 30 percent and less correspond to preference indices of zero.

CHANNEL MODIFICATION PRACTICES AND COSTS

Background Information

Extensive drainage improvement projects were conducted in Illinois from the mid-1800s through about 1950. Channels were created by digging and dredging to drain swamps and marshes for agricultural production. Existing streams were widened and deepened to accommodate the increased runoff. Today most rural channel modification projects are initiated to clear and maintain the channel network. In urban settings, increasing peak discharges from continuing establishment of more impervious areas and accelerated sewer drainage may create the need to increase the carrying capacity of channels to avoid flood damage.

Engineering and construction practices for channel modification to improve drainage and abate flooding, as well as environmental and economic aspects of channel modification, are described in *Channel Modification: An Environmental, Economic and Financial Assessment,* a report to the Council on Environmental Quality, Executive Office of the President (Little, 1973). The statewide extent of stream channelization in Illinois is documented in the Illinois Streams Information System database on stream characteristics (Riley et al., 1985a, b). It is estimated that one-third of the interior streams in Illinois have been channelized or otherwise hydraulically modified (IEPA, 1979). In 1988 the IEPA reported that 3,749 miles out of a total of 12,970 channel miles assessed were impaired as a result of these modifications (IEPA, 1988). Channel modifications and maintenance of streams with small drainage areas are usually performed under the auspices of local drainage districts (organized to promote drainage improvement) which govern in rural areas and often share overlapping jurisdiction with communities. Under the provisions of Section 404 of the Clean Water Act, a permit program administered by the Corp of Engineers has been established to regulate discharge of dredge or fill materials into streams and rivers (IEPA, 1989). The Illinois Department of Conservation (IDOC), the Illinois Department of Transportation, Division of Water Resources (DWR), and the Illinois Environmental Protection Agency (IEPA) must also review and approve all permit requests for proposed construction involving Illinois streams.

Traditional channelization practices have a significant and usually detrimental impact on the stream ecology, altering the aquatic habitat to the extent that it can no longer support many desirable aquatic biota. Construction of straight uniform channels eradicates riffle-pool sequences. These sequences provide a diversity of flow conditions required by various fish species at different life stages as well as by organisms on which they feed. Pools provide protected areas for fish during high flows. Natural sorting of bed materials with coarser material at riffles and finer material in pools is obliterated by creating uniform channel reaches, disrupting the habitat needed for many organisms in the food chain and used by some fish species for spawning. Clearing of debris and vegetation from banks to decrease flow resistance and to provide equipment access eliminates natural cover for aquatic organisms. Beschta and Platts (1986) describe features of small streams such as riffles, pools, and substrates as well as their function and relation to habitat suitability.

The adverse impact of stream channelization has been well documented by numerous case studies of streams nationwide. Brookes (1985) gives an overview of engineering methods and consequences of channelization practices as well as alternatives to channelization. Identification of specific stream habitat characteristics that are lost through conventional channelization procedures provides insight into possible beneficial restorative measures and less detrimental construction practices.

Typical assessments of the causative factors leading to degradation of the aquatic habitat, such as those noted in the preceding paragraph, are illustrated by specific studies conducted in and near Illinois. A comparative study of natural streams which have never been dredged, old ditches which have not been dredged for at least 50 years, and new ditches which have been dredged since 1967 was conducted in Buena Vista Marsh, Portage County, Wisconsin (Schmal and Sanders, 1978). The study demonstrated that the disruption of channel substrates caused by channelization was detrimental to the populations of benthic organisms and aquatic insects, which are critical in the stream ecosystem food chain.

The effect of stream channelization on macroinvertebrates and fish was studied in four rivers in Ohio (Olentangy, Sandusky, Hocking, and Little Auglaize) and in Rock Creek in Indiana by Griswold et al. (1978). A channelized and a natural reach were studied in each river, and the abundance of desirable aquatic life forms was compared. The fish species studied (including smallmouth bass, sunfish, channel catfish, and crappies) are typical of central Illinois streams (Herricks and Himelick, 1981; Herricks et al., 1983). Griswold et al. (1978) found that the abundance and diversity of both macroinvertebrates (e.g., insects) and high-value fish are frequently severely reduced by channelization. The loss of desirable benthic organisms is attributed to the deposition of unstable bottom material, especially in silt-laden warm-water streams draining agricultural lands. Game fish are replaced by non-game fish, which is attributed to the loss of riffle and pool environments and diverse substrate.

Portions of the Vermilion and Embarras Rivers in Illinois have been extensively channelized and their flow regimes altered. A comparison of fish species taken prior to 1901 and between 1956-1966 showed extensive loss of high-value fish species populations (Smith, 1968). Smith concludes from his study of the basin character and stream fisheries that alteration of the physical habitat (e.g., rate of flow and bottom type) were of greater significance than pollution in producing the long-term changes in fish populations. In their study of Gordon Creek in Ohio, Trautman and Gartman (1974) link the reduction and/or loss of various fish species in the stream to the elimination of various habitat characteristics, such as cover, substrate, and riffle-pool sequences, resulting from channelization. Fish populations in channelized and unchannelized sections of the Chariton River (Missouri) were studied by Congdon (1971) to determine differences in diversity of species and size. The results demonstrated a decrease in both diversity and size of game fish. Congdon concludes that the standing crop of catchable-size fish was reduced by 89 percent in the channelized section in comparison to the unchannelized study area.

Over the last two decades there has been an increasing awareness of the consequences of traditional channelization techniques: the adverse impact on the stream ecosystem, erosion, and sedimentation problems. The IEPA has initiated a four-year program to establish a review process that defines specialized procedures and criteria to protect Illinois waterways from improper modification (IEPA, 1989). Various studies have been conducted to explore the effectiveness of rehabilitating previously channelized streams by re-creating some characteristics of the natural channel that are critical to establishing an environment that can support desirable fish species. In light of pressures to protect stream ecosystems, drainage improvement projects have increasingly incorporated techniques that reduce or ameliorate the consequences of increasing channel carrying capacity. The scope of ameliorative measures taken ranges from minimizing the disruption of the channel during clearing to complete restoration to approximate natural conditions.

A wide variety of techniques have been employed to enhance the aquatic habitat of disturbed streams. Some procedures have proven successful, while others have not. The intent of this report is not to provide a detailed evaluation of the effectiveness of various techniques, but to examine the cost of various channel modification practices which have proven at some level to be effective in enhancing the aquatic habitat. In particular, techniques to re-create a riffle-pool structure have been investigated. Bank stabilization is an intrinsic aspect of channel rehabilitation. An in-depth study of various stabilization techniques is beyond the scope of this investigation, but some information is provided on practices found to be successful in Illinois.

Channel Modifications for Habitat Enhancement

Stream habitat may be defined in terms of components that relate directly to the needs of aquatic organisms: channel substrate, vegetation, flow velocities and depths, cover, temperature, and general water quality. Stream improvement projects may address all or some of the components of the aquatic habitat. The IEPA identifies 21 different Best Management Practices for hydrologic/habitat modification, including structural modifications such as in-channel check dams, riprap, and vegetative bank protection; livestock exclusion; selective dredging; and protection of existing vegetation (IEPA, 1989). Design of the physical channel structure to incorporate some of the characteristics of natural streams, such as riffle-pool sequences, directly affects several of the habitat parameters, specifically velocity, depth, and substrate gradation.

Several types of artificial, in-channel structures are commonly used for habitat enhancement. *Current deflectors* assist in the development of meander patterns, protect streambanks from erosion, and enhance riffle-pool ratio, among other purposes. *Check dams* deepen pools, encouraging gravel bar formation for spawning below the structure, and slow the current, thereby allowing organic debris to settle out and promote invertebrate production. *Boulder placement* promotes fish cover, improves riffle-pool ratios, and restores meanders and pools (Wesche, 1985; Starnes, 1985). Wesche (1985) cites examples of successful applications of deflectors, dams, and boulders in several states and defines general guidelines for the placement of structures and the use of construction techniques. Klingeman (1984) discusses the design of habitat modification structures such as gabion deflectors, weirs, and boulders. Gore (1985) offers additional examples of the use of man-made structures for depth and velocity alteration as well as substrate manipulation. A series of five rock-and-boulder artificial riffles proved successful in reestablishing populations of game fish in a previously channelized section of the Olentangy River near Columbus, Ohio (Edwards et al., 1984). More extensive examples of stream restoration, where the natural sinuosity of the channel is re-created, are given by Brookes (1987) and Keller and Brookes (1984).

Reestablishment of aquatic invertebrate communities, which form an important link in the food chain, requires creation of suitable substrate conditions. Gore and Bryant (1988) report that the greatest diversity and production of aquatic invertebrates are reported from channels with substrate composed of medium cobbles (256-mm diameter) and gravel. They further explain the roles of riparian vegetation, substrate, and channel structures for river and stream restoration. The relation of substrate to aquatic invertebrate production and the availability of a major food resource for warm-water stream fishes in the Midwest is discussed by Angermeier and Carlson (1985). From their study of aquatic invertebrates in Jordan Creek, tributary to the Vermilion River in east-central Illinois, they found that substrate composed of gravel and cobbles provided a more abundant and stable food base for warm-water fish (characteristic of small midwestern streams) than substrate composed predominantly of silt and sand.

Channel maintenance work is frequently desirable in removing obstructions such as fallen trees and significant accumulations of sediment which interfere with streamflow and create flooding problems. Guidelines for correcting streamflow problems created by obstructions in an environmentally sound manner and for maintaining natural stream characteristics have been prepared by the Stream Renovations Guidelines Committee of the Wildlife Society and American Fisheries Society in cooperation with the International Association of Fish and Wildlife Agencies, American Fisheries Society (1983). In situations where stream work must be performed, it is recommended that channel excavation and debris removal be performed with the use of hand labor and hand tools such as axes, chain saws, and winches, to minimize disturbance of streamside vegetation. If the task cannot be accomplished with hand labor, rubber-tired vehicles such as small tractors, backhoes, and bulldozers are recommended. Heavier equipment such as draglines is to be used only in extreme cases. Other practices promoted are selective tree removal only to the extent required for equipment access, and working on only one side of the channel to preserve cover and vegetation on the undisturbed bank. Disturbed areas are to be restored by reseeding and/or vegetative bank stabilization. Some of these practices are currently being adopted in routine channel maintenance work in Illinois. The concept of maintaining natural sections of a stream (whether undisturbed or restored) within major channelization projects is discussed by Griswold et al. (1982). Stream sections having habitat attributes such as riffle-pool sequences and cover could serve as a refuge for aquatic life during stressful streamflow or climatic conditions. They could also serve as a source for repopulation of channelized reaches temporarily impacted by construction or adverse climatic conditions.

Cost of Channel Rehabilitation

The cost of various channel rehabilitation methods varies with the extent of the modification, the size of the stream, and the availability of materials. Other factors which influence the cost of projects are the professional engineering design fees and the personnel hired to perform the work. To investigate the cost of channel modifications, information was collected through a literature search of technical reports on projects designed for habitat enhancement, meetings, and phone conversations with drainage engineers and project managers from various government agencies involved in channel restoration programs. The cost information obtained is presented in two formats. First a brief description of selected projects is provided, with specific information on stream location; size, extent, and objectives of the channel modification project; procedures; and costs. Projects described include pilot studies of various habitat enhancement concepts, as well as traditional channel maintenance work for comparison. Secondly, to the extent possible, the information is summarized in a tabular format with unit costs.

The cost of channel modification projects sponsored by drainage districts or municipalities is typically estimated and bid by contractors on the basis of unit cost for various components of the work such as excavation, clearing, and seeding. This format, which was adopted for summarizing the data where possible, provides data somewhat independent of the scope of the project (although economies of scale do have some impact). To provide a common basis for cost comparison, costs were adjusted to 1989 dollars on the basis of cost trends in quarterly reports in *Engineering News Record,* herein referred to as ENR cost indexes.

Itemized costs are not available for many of the pilot programs, as these may be conducted by government agencies or through research grants and not bid on a unit-cost basis. Materials may be donated and labor hours not accounted for. Typically when cost information is available for these types of projects, it is a total project cost. To provide some means of cost comparison, a dollar cost was calculated per foot of stream length affected. This, together with the information on drainage area, location, and purpose of the project provided in the summary of case studies below, gives a basis for comparing different approaches.

Case Studies

The descriptions provided below are summaries of pertinent information regarding various stream modification projects. They summarize a variety of types of projects, which reflect different purposes for the work and different levels of stream modification practices with regard to habitat protection and/or enhancement. The information is provided to aid in interpretation of cost data available for these projects. The information was obtained from published technical reports, engineers' reports, contract documents and plans, and personal communications.

Hurdvgurdv Creek (Moreau, 1984). Hurdygurdy Creek is a fifth-order stream tributary to the South Fork Smith River in northwestern California. The drainage area of the creek is approximately 30 sq mi, and it is about 14 miles long. Prior to restorative work, the study area had wide shallow riffle sections lacking defined thalwegs and containing uniform cobble substrates. Approximately 0.8 mile of the lower 3.9 miles of the creek was modified by the placement of mid-channel boulder clusters, wing deflectors, and weirs. All were constructed by a rubber-tired front-end loader from boulders stockpiled at the stream margin. Two boulder weirs, 3 excavated rock deflectors, 22 boulder deflectors, and 154 boulder clusters were constructed with a total length of treated area of 0.8 mile of stream length. Mid-channel boulder clusters consisted of at least three boulders and were approximately 3.0 to 4.0 cu m (106 to 141 cu ft) in total volume. Wing deflectors varied in length from 6.1 to 13.7 m (20 to 45 ft), ranged from 1 to 2 m (3.3 to 6.6 ft) in width, and were about 1 m (3.3 ft) in height. Weirs were approximately 4 m (13 ft) wide, 1 m (3.3 ft) high, and spanned the channel, approximately 25 m (82 ft). Boulders used were approximately 0.3 to 3 cu m (11 to 106 cu ft) in volume. Rock deflectors constructed of streambed rock (cobbles to 60 cm) were 5 m (16.4 ft) long, 1 m (3.3 ft) wide, and 1/2 m (1.6 ft) high; with these dimensions, a rock deflector is about 2.5 cubic meters or 88 cu ft. The in-place cost of boulders ranged from $41 (1981) to $77 (1983) per cubic meter ($1.16 to $2.18 per cu ft). The cost increase was primarily due to the development of a quarry for the boulders; future costs were expected to be lower. The estimated 1989 cost range is $1.29 to $2.33 per cu ft with an average cost of $1.81 per cu ft. The cost of individual structures described in the report was calculated on the basis of $1.81 per cu ft and is presented in Table 13. The total project cost was not stated. However, the cost per foot of stream length in the treated areas may be estimated on the basis of the number of structures placed and the average cost for a typical structure. The approximate cost is in the range of $5 to $13 per foot of stream length, but this is a rough estimate reflecting average conditions, not actual reported cost.

Alkali Creek (Heede, 1966). Alkali Creek, a tributary to the Colorado River in Colorado, was selected for a detailed study of the cost of four different designs of rock check dams. Check dams were constructed in nine gullies, with widths ranging from 5 to 50 feet and depths from 2 to 30 feet. Quarry rock with diameters ranging from 0.3 to 1.0 foot as well as boulders up to 3 feet in diameter were used. Heede details a breakdown of material volume for each structure, machine time, and labor time. While

Table 13. Unit Cost for Stream Channel Modification

Item	*Unit of measure*	*Estimated 1989 cost*	*Range of cost*	*Notes*
Excavation	cuyd	$1.58	$1.07 - $2.98	(1)
Clearing	acre	-	$208 - $2350	(2)
Seeding	acre	$400	$225 - $1000	(3)
Seeding & mulching	acre	$911	$350 -$1500	(4)
Spraying	mi	$482	$162 - $821	(5)
Riprap	ton	$17	$11-$32	(6)
	cuyd	$24		(7)
Sediment trap	each	$960	$250 - $3100	(8)
Gabions (12" deep)	sqyd	$34		(7)

Special Structures

	Estimated 1989 cost		
	cu yd	*cu ft*	
Rock check dams			
Loose rock	$47	$1.74	
Wire bound	$75	$2.78	(9)

	Estimated 1989 cost		
	Average	*Range*	
Boulders, clusters, weirs, wing deflectors	$1.81 cu ft	$1.29-2.33 cu ft	(10)

Example Structures: (estimated cost at $1.81 cu ft)

	Dimensions	*Cost*
Boulder cluster	106 to 141 cu ft	$192 - $255
Wing deflector	20 ft × 3.3 ft × 3 ft = 198 cu ft	$358
	45 ft × 6.6 ft × 3 ft = 891 cu ft	$1613
Weir	13 ft ×3 ft×l ft = 39 cuft	$71*
Rock deflector	16 ft × 3 ft × 1.5 ft = 72 cu ft	$130

*per foot of stream width

Table 13. Concluded

Item	Estimated 1989 cost: Average bid	Range of bids	Notes
Fish-pool log covers, each	$665	$250-$2000	(11)
Fish-pool log covers, pool excavation, riprap (completed projects, contract labor, and materials)		$2000 -$2500	(12)
Lunkers (underwater fish habitat structures)	$10 per linear ft of channel		(13)
Dormant willow post bank protection	$4 per linear ft of bank		(14)
Tree revetments	$4 per linear ft of bank		(14)

Notes (costs are given in estimated 1989 dollars):

(1) Average cost determined from over 20 contractor bids on 4 projects in rural areas

(2) Range of cost for light to heavy clearing estimated from 10 contractor bids

(3) Average cost determined from over 20 contractor bids of 5 projects in rural areas

(4) Average cost determined from 15 bids on 2 projects in rural areas, engineering estimate for fine grading, mulching, fertilizing, and seeding in urban areas ($5,000 per acre)

(5) Spraying of herbicides to inhibit woody plant growth, average cost determined on the basis of 9 bids for 2 projects in rural areas

(6) In-place cost, cost varies depending on transport distance; cobbles delivered may cost only $10 to 18 per ton (Condit and Roseboom, 1989)

(7) Published cost adjusted for location and 1989 cost increases from Mahoney (1987)

(8) Average cost determined from over 20 bids on 4 projects, cost varies with stream channel size

(9) Estimated 1989 cost on the basis of design and material and labor requirements given by Heede (1966)

(10) Estimated 1989 cost on the basis of descriptions from Moreau (1984)

(11) Average bid for work determined on the basis of 14 bids; Indiana stream restoration projects (B. Beard, SCS, personal communication)

(12) Range of cost estimated on the basis of completed contract work for structures designed for Indiana stream restoration projects (McCall and Knox, 1978); specific data provided by B. Beard, SCS, personal communication

(13) For description of structures, see summary of Court Creek project (Condit and Roseboom, 1989)

(14) Court Creek Project (Condit and Roseboom, 1989)

the construction of rock check dams on steep gradient slopes (3 to 18 percent) is not directly applicable to Illinois streams, the detailed information on machine and labor time to place a given volume of rock is instructive. Current labor and machine charge time was applied to the information given for the construction of loose rock check dams and wire-bound check dams. The calculated costs are listed in Table 13.

South Fork Salmon River (West, 1984). The South Fork Salmon River is located in California. Approximately 4,000 feet of the river was modified by the placement of boulders to create scour pools and provide a diversity of habitats and substrates. Rubber-tired front-end loaders were used to place the boulder groups. The boulders ranged from 3 to 5 feet in diameter, and had an average weight of 5,400 pounds. Eight triangular wing deflectors and 180 boulder groups were placed for a contract cost of $43,000, or approximately $11 per linear foot of improved channel. On the basis of general ENR cost indexes for canals and earthworks in 1984 and 1989, the 1989 estimated cost is $12 per linear foot of improved channel.

Olentangv River (Edwards et al., 1984). The Olentangy River is tributary to the Scioto River in Ohio. It has a drainage area of 536 sq mi and is 88.2 miles long. In 1970 a section of the river 10.9 mi upstream from the mouth was modified to accommodate the construction of an interstate highway. To mitigate the impact of the relocation, a series of artificial pools and riffles was constructed. Five riffles were constructed by layering boulders over earthen fill. The riffles are about 20 feet wide and extend about 118 feet from bank to bank. Pools are around 800 feet in length with a maximum depth of about 8 feet at mean flow. The modified section is about 4,500 feet in length. The cost in 1970 of constructing the riffle-pool sequences was $65,000, or about $14 per foot of stream modified. The estimated 1989 cost is $186,550 or $41 per foot of stream modified (Ron Schafer, Ohio Division of Fisheries, personal communication, Dec. 12,1988). A study of the abundance of game fish in this mitigated reach compared to a natural section and an unmitigated section of the river demonstrated that the fish population was similar to that in the natural area and much more abundant than in the channelized section (Edwards et al., 1984).

Mecklenburg Restoration Project (Nunnally and Keller, 1979). Experiments with stream restoration have been conducted on more than 34,450 feet of stream length in five different streams in North Carolina. Projects were administered by the County Engineer and were funded by the county. These previously channelized streams are in an urban setting and had become clogged with debris and overgrown with trees. The purpose of the project was to restore flow efficiency in the streams and provide a stable channel. The restoration plan involved morphologic design of the channel dimensions, and stabilization of the banks with riprap and vegetation, while preserving meanders and as many trees as possible. Thus the project represents the integration of procedures to preserve a semblance of the natural setting while improving drainage. The Briar Creek renovation (downstream drainage area of 10.1 sq mi) is typical of the type of work conducted and is discussed at length in the report. The reported cost of the renovation projects including materials, wages for a 14-man crew, equipment, and equipment operation and maintenance was $8 to $22 dollars per linear foot depending on the stream conditions, channel size, and amount of riprap required. The estimated 1989 cost range is $14 to $39 per linear foot of channel, with an average of $26.5 per linear foot.

Court Creek Project (Condit and Roseboom, 1989). Through the Illinois Department of Conservation's Watershed Planning Program, development of low-cost streambank erosion control methods (based on vegetative streambank stabilization) has been studied on Court Creek in the Illinois River Basin (drainage area 97.5 sq mi). The project was conducted by the Water Quality Section of the Illinois State Water Survey. Court Creek was experiencing severe bank erosion problems as a result of channelization which had removed meanders and increased velocities. Two different procedures for tree revetment were employed. George Palmiter, a private contractor, has developed methods of stream rehabilitation on the basis of observations and trial-and-error experimentation. His practices and previous projects conducted in Ohio have been reviewed by Willeke and Baldwin (1984). George Palmiter was employed to install tree revetments along a 3-mile segment of the project. Several of the sections treated using the Palmiter method failed, and the Knox County Soil and Water Conservation District (SWCD) replaced them with tree revetments using Laconia anchors and hedge trees. Dormant willow posts were planted along two reaches.

Bank erosion was significantly reduced by each stabilization technique. However, tree revetments placed by George Palmiter in severely eroding areas had to be replaced by using the more substantial anchoring method. The cost per linear foot of bank for each method was: Palmiter tree revetments, labor and materials $3.73, technical assistance $4.27; SWCD tree revetments $3.00; dormant willow post $3.10. Performance of the last two methods by a private contractor is expected to increase cost to about $4.00 per linear foot to allow for a profit margin. Technical assistance from a professional consulting firm for the tree revetment or willow post stabilization techniques is estimated to range from $1.00 to $5.00 per linear foot, depending upon site difficulties. Dormant willow posts have also been used in Court Creek in the construction of underwater fish habitat structures, referred to as lunkers. The lunkers consist of wooden pallets 8 by 4 feet anchored with about nine pieces of 8-foot-long iron bar; banks are sloped at a 1 to 1 ratio, and additional bank cover is provided with riprap and willow posts. The structure forms a pool, and a gravel riffle forms downstream. The structure has proven successful at Court Creek and is planned for other projects. The structure cost approximately $10.00 per linear foot of bank.

Indiana Channel Modification Program (McCall and Knox, 1978). In Indiana, through a joint effort between the State Department of Natural Resources, the U.S. Fish and Wildlife Service, and the Soil Conservation Service, channel modification guidelines have been developed and implemented which protect or mitigate losses of fish, wildlife, and riparian habitats resulting from channel work for flood damage reduction and drainage. The various practices developed were initially implemented in five projects on streams with small drainage areas (estimated drainage area less than 100 sq mi). Practices employed in the various projects reported by McCall and Knox included use of hand tools and small machinery for removal of fallen trees, logjams, and other debris which restricted flow; use of a small boat and log skidder to remove logjams; construction of fishways of pools and riffles in a previously channelized river (earthen channel pools were dug 2-1/2 to 4 feet deep, and 6-inch-deep riffles were constructed with riprap); use of rock deflectors to maintain fish pools; sediment traps to prevent sediment from leaving construction sites; and revegetation of banks. Other practices involved clearing and channel work performed from one side of the stream only to avoid disturbance of the other bank, fencing off creeks to protect them from livestock damage, and maintenance of shade by the preservation of hardwood trees.

Fish studies conducted before and after completion of projects involving the creation of pools showed a marked increase in desirable fish species populations, including several species of bass and longear sunfish. Inspection conducted five years after construction showed that deflectors were still functional and maintaining fish pools. Success of these projects has led to further implementation of similar practices in channel modifications caused by highway bridge construction and county drainage maintenance. Two projects have recently been undertaken for which detailed cost information was provided by Bill Beard, U.S. Department of Agriculture (USDA) Soil Conservation Service (personal communication, February 13, 1989). A 7-1/2-mile length of channel of Twin Rush Creek (drainage area 43.9 sq mi) was modified in 1986, and 5 miles of channel on the Upper Big Blue Watershed (drainage area 25.7 sq mi) were modified in 1988. The 1989 cost per foot of stream length was estimated on the basis of the three lowest bids for each project. Excluding tile and structure repair, the cost for items including but not limited to excavation, clearing, seeding, riprap, and fish pools was approximately $39 per foot for Twin Rush Creek and $19 per foot for the Upper Big Blue. The major factor contributing to the cost difference is that about four times more excavation was required for Twin Rush Creek than for the Upper Big Blue. In addition to some channel excavation and bank stabilization, fish pools with log covers and boulder deflectors in combination with a downstream riffle were constructed. The average bid for installation of fish-pool log covers was $665 each. Fish-pool log covers on large streams may run from $1,000 to $2,000. Riffles 25 feet long were constructed of cobbles 2 to 5 inches in diameter at a cost of about $900 per riffle. The excavation cost for pools varies with stream width (ranging from 10 to 34 feet in the Upper Big Blue Project), and the average cost of the pool and riffle sequence, including all materials and labor, runs from $2,000 to $2,500. Construction details of the log deflector, fish pool, and riffle designed by the USDA Soil Conservation Service are shown in Figure 20. Both projects were bid by private contractors. The range of bids for the construction of the fish-pool log covers is given in Table 13.

<u>Illinois River Soil Conservation Task Force</u> (Condit, 1989). The Illinois River Soil Conservation Task Force was formally founded in 1985. The Task Force has been involved with the testing of low-cost gully and streambank stabilization techniques. Four projects have been completed on Illinois streams. Methods of bank stabilization employed include tree revetments, willow post plantings, and the use of tire structures. Through a combination of tire structures (48 structures) and living willow structures (4 structures), 1,001 feet of main channel and 737 feet of ravines were treated at a cost of $10.65 per linear foot. Individual tire structures cost $347 on the average, and willow structures $463. Personnel to install the structures were employed through the Public Aid Project Chance program. Wages for laborers employed by private contractors will increase cost, as will profit margins added by private concerns.

<u>Southwood Second Section of the Phinnev Branch Mutual Drainage District</u> (Plans and specifications by Altech Consultants, Champaign, IL, 1985). The Southwood Second Section of the Phinney Branch has a watershed of approximately 3.75 sq mi. Approximately one-half of the upstream portion of the drainage area is in

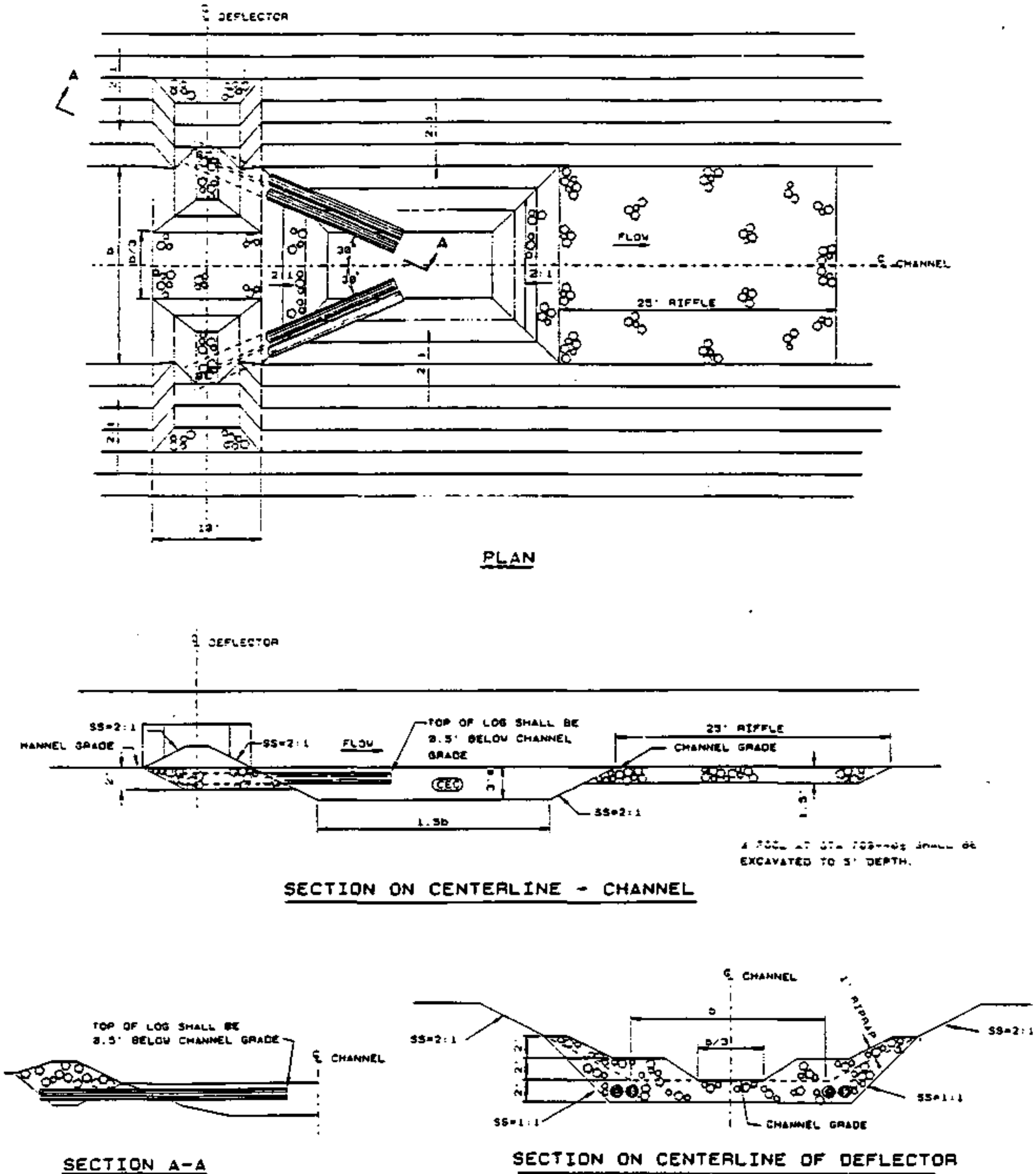


Figure 20. Construction details for artificial riffle-pool aquatic mitigation feature designed by USDA Soil Conservation Service, Indianapolis, Indiana

agricultural use, and the remaining downstream area is primarily a residential, urban area. Proposed channel modification work designed by the engineering firm Altech Consultants covers 2,000 feet of channel that flows through an entirely residential area. The 2,000-foot section is estimated to have a carrying capacity sufficient to pass a 2- to 5-year design frequency storm, while upstream and downstream sections have been modified to flow capacities capable of carrying a flood approximately equal in magnitude to a 100-year frequency event. In addition to typical excavation, bank protection, and seeding, the project work includes utility rerouting; replacement of carports, sheds, and driveways; placement of sod and trees; and shrub replacement needed because of the residential use of the adjoining area. The total project cost is estimated to be about $200 per linear foot. Excluding utility rerouting and structure replacement, the estimated cost was $175 per linear foot. Much of the cost is attributable to landscape replacement and easement acquisition. Clearing and excavation of the channel and bank protection represent approximately half the total projected cost as of May 1990.

Nelson-Moore-Fairfield Drainage District (Plans and specifications by Altech Consultants (formerly Bazzell-Phillips and Assoc.), Champaign, IL, 1984). The Nelson-Moore-Fairfield Drainage District is located in Champaign County, Illinois. The main ditch in the primarily agricultural drainage district serves as an outlet to the underground drain tile network, beginning at the headwall terminus of the collector drain tile. The drainage ditch extends approximately 4.6 miles from the tile outlet to the Sangamon River. In 1985 work designed by the engineering firm Altech Consultants (formerly Bazzell-Phillips and Assoc.) was performed on this main ditch to provide greater carrying capacity. Typical of most channel maintenance projects, the work included removal of all trees, brush, deadwood, broken concrete, and debris from the entire channel width and work area; restoration of slopes and banks to original dredged trapezoidal cross sections; and reseeding for bank stabilization; as well as miscellaneous outlet tile repair. On the basis of ENR cost indexes for earthwork, the 1989 estimated costs for channel work only (excluding repair of drainage tiles) is $1.05 per linear foot of stream length. This cost does not include a performance bid bond.

Deer Creek Watershed. Kemp Drainage District (Plans and specifications by Berns, Clancy and Associates, Champaign, IL, 1986). The Deer Creek watershed lies in Douglas and Coles Counties in east-central Illinois. The total drainage area of the watershed is approximately 43 sq mi, and the area affected by the project is about 35 sq mi. Land use is primarily agricultural. Land surveyors' notes taken in the late 1820s indicate that only the lower 3 miles of Deer Creek above its confluence with the Embarras River existed at that time. The land was claimed for agriculture through a network of tiles and dredged open ditches to drain marshes and ponds. Six-and-one-half miles of Deer Creek were created by dredging in the 1800s. Prior to 1986, the last work on the Main Ditch of the Deer Creek Outlet and its two main tributaries (the Kemp Branch Main Ditch and the Arcola Branch Main Ditch) was performed around 1949 and did not include the lower 4 miles of Deer Creek. Accumulation of woody and brushy vegetation, driftwood, logs, sand bars, and silt within the channel since the 1949 channel work was impairing drainage from farmland and several small communities and was creating flooding problems in agricultural areas.

The 1986 channel maintenance project employed construction practices to reduce adverse impacts of the channel clearing work, including limiting the clearing of trees and vegetation adjacent to the waterway to only the amount necessary to provide access. Generally work was performed from one side of the ditch; dredging activity was timed to avoid disturbing the channel during the spawning season of fish species identified in the area; silt traps were constructed to limit sediment discharge downstream of the project area during construction; and riprap was used to protect channel side slopes at drain tile outlets. On the basis of bids from three general contractors and with the cost adjusted by using ENR cost indexes, the average bid total project cost of maintenance work for 3.1 miles of the Kemp Branch, 1.3 miles of the Arcola Branch, and 6.7 miles of the Deer Creek Main Outlet is about $7.80 per linear foot of stream. This figure does not include the repair and replacement of field tiles and other drainage structures or the performance bond. The contract performance bond averaged around 2 percent of the total project cost.

<u>Drainage District No. 2 of the Town of Areola</u> (Plans and specifications by Berns, Clancy and Associates, Champaign, IL, 1986). The Areola Drainage District is located in east-central Illinois and has a total area of about 10.2 sq mi. Natural drainage is provided by Deer Creek and its tributaries. The land within the drainage district is almost entirely devoted to agricultural use. Much of the area would be swamp or ponds except for the drainage maintained by field tiles and excavated open ditches. There are few hardwood trees in the area. Drainage ditches were originally excavated in 1927, and some maintenance work was performed in 1945. The drainage improvement project financed by the district in 1976 involved clearing of woody and brushy growth within channels and clearing of sand bars, silt and debris, as well as repair of outlets

for the system of underground tiles, and correction of erosion problems associated with deterioration of outlets. The project includes work on approximately 1.5 miles of the Main Ditch Deer Creek Outlet, one mile of the Filson Branch, and 2.3 miles of the Arcola Branch. (The Filson and Arcola Branches are both tributary to the Main Ditch.) The work is typical of that required to maintain agricultural drainage by improving channel conveyance capacity to accommodate a 5-year return interval runoff event. The project work includes excavation, tree clearing, seeding of excavated banks, spraying of ditch side slopes with a herbicide to inhibit woody growth, construction of silt traps to trap sediment during excavation work, fence removal and replacement, and repair of numerous drainage tile outlets. A contract performance bid bond was also required. On the basis of bids from six contractors, the average bid was $3.07 per linear foot of the channel. Excluding the performance bid bond and the tile outlet repair, which varies considerably from channel to channel, the average bid was $2.32 per linear foot and the low bid was $1.81 per linear foot. The performance bond averaged 1.7 percent of the total project bid.

<u>Agricultural Drainage District Channel Modification Projects.</u> The Nelson-Moore-Fairfield Drainage District and Drainage District No. 2 of the town of Areola are typical of projects to maintain open-ditch drainage in agricultural areas. Cost data for other similar projects were collected. However, the project work is similar to that described in the previous two cases and will not be detailed herein. The drainage areas of the streams and the contract cost per linear foot for channel work only, excluding bid bond and outlet tile repair and adjusted to 1989 cost using ENR cost indexes, are as follows: drainage area 11.6 sq mi, $4.39; drainage area 19 sq mi, $2.83. Engineers' estimated cost per linear foot of channel for three other projects are: drainage area 6 sq mi, $3.26; drainage area 10.6 sq mi, $5.56; drainage area 130 sq mi, $15.00. The cost increases with the amount of sediment which must be removed, which generally increases with the size of the stream.

Unit Cost for Channel Modifications

Unit costs for various components of channel modification work are presented in Table 13. The dollar values presented are estimated 1989 costs for work performed by private contractors. Notes explain the source of the information or provide a reference to more detailed information on the particular item. Some cost data are averages of several bids by private contractors from different projects. For a particular project, the contract will typically be awarded to the lowest overall bidder, not necessarily on the basis of the low bid on any specific item shown in Table 13. Therefore the range of bids for a particular item is given in cases where the data were available. Some specialty structures have been constructed only a limited number of times. In such cases, the notes provided indicate the project from which the cost data were obtained, which should lend some insight into the particular conditions. In some cases only final cost data for awarded contracts were available, and this is indicated in the description or note.

Summary

The cost data provided for each case study and the unit cost presented in Table 13 may be used as a guide for the relative cost of various types of channel modification work. The cost varies for each project depending on the size of the stream channel, the condition of the stream channel, and the land use adjacent to the stream channel. Generally the cost will increase with channel size, and costs are greater if a large amount of undesirable debris and sediment has accumulated. Except as noted, the cost given for the particular studies is believed to represent work performed by private contractors. Pilot studies conducted by a government agency or research organization often may have considerably lower labor costs, as they may hire temporary personnel and may have the advantage of donated materials. Work performed for drainage districts or county agencies typically must be performed by private contractors and secured with some form of performance insurance. Standard builders risk insurance averages between 0.19 to 1.14 percent of the contract work (Mahoney, 1987). Other factors which must be considered are engineering design fees and project supervision. As a rule of thumb, engineering fees for a typical drainage project following standard design procedures will run around 10 percent of the project contract cost. Departure from standard design principles and applications of a relatively new or theoretical design will require more engineering time. The more extensive the restoration aspects of the project, the more engineering time is required. In addition to the design aspects of an environmentally sensitive channel modification project, on-site supervision of work crews by the engineer or representative is recommended when new designs or methods are being employed. This represents an added cost, as standard channel work (clearing, excavating, etc.) is generally performed at the discretion of equipment operators, with completed work inspected by engineers or their representatives.

CONCLUSIONS

The relationship between discharge and drainage area varies with flow duration. Examination of coefficients defining the relationship between discharge and drainage area shows two distinct flow regimes. For the Sangamon Basin, there is a consistent variation of discharge with drainage area and flow duration for annual flow durations from 10 to 50 percent. There is also a consistent, but different, relationship between these parameters for annual flow durations from 60 to 90 percent. A new form of hydraulic geometry equations where the coefficient for the parameter log(DA) varies with flow duration satisfies the condition of continuity. Development of two sets of hydraulic geometry equations for each flow regime provides a good approximation of W, D, and V for both high and low flows.

On the basis of laboratory grain size analysis, there is little difference in riffle material for streams in the Sangamon Basin with drainage areas between 50 and 300 sq mi. The observed grain size of materials forming riffles in streams throughout the basin appears to be influenced by differing physiographic regions within the basin, the presence of moraines, and local disturbances of the channel. Differences in median grain size from multiple samples taken at a single riffle demonstrate that a single sample may not provide an adequate representation of the riffle bed material.

Penetrometer measurements appear to have fairly good correlation with grain size and laboratory-measured dry density of subsurface bed material. The bed material density and penetrometer data show that the material at the riffles is consistently more compact than in the pools. Further, in pool areas the depth below the bed surface reached with the penetrometer suggests that the loose material in the pools may be flushed by high flows. Much greater depths, relative to adjacent riffles, may be observed at high flows than occur at lower flows when there is a greater accumulation of silt. Results of grain size analysis as well as observation of materials in the pits dug at riffles show that riffles are armored with coarser material at the surface.

Comparison of average flow depths at riffles and pools, standard deviation of measured depths, and bed elevation survey data demonstrate the definite link between the standard deviation of depth used in the flow model and the relative elevations of riffles and pools.

Incorporation of substrate in the basinwide flow and habitat model provides a more complete definition of the stream habitat for assessment of its suitability to support various fish species. The model can be used to demonstrate the availability of suitable habitat for various flow durations for comparison to proposed modifications in the channel.

Channels constructed to improve drainage of farmland and streams subject to increased peak flows resulting from urbanization require periodic maintenance to assure adequate performance of their flood control function. The cost of routine channel maintenance work depends on the amount of sediment which has accumulated. Bank stabilization using dormant willow posts and revegetation, which helps reduce erosion and hence downstream sedimentation, is less costly than installation of riprap or gabions. Other habitat-enhancing features such as the placement of boulders to create scour pools or more elaborate reconstruction of riffle-pool sequences are an added cost to a project. The erosion-reducing potential of a morphologically balanced stream structure needs further investigation.

Restoration of riffle and pool features in previously channelized streams can lead to an enhanced aquatic environment suitable for the support of various desirable fish species. Information defining channel characteristics, such as width-to-depth ratio, riffle-to-riffle spacing, proportions of riffle and pool areas in a stream, and the difference in elevation from riffle to pool, provides basic data which can be used to design restorative features consistent with natural stream development and morphology of the basin. Morphologic design of these features is expected to provide a more stable channel configuration.

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